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Geotechnical and Structures Laboratory

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Evaluation of Recharge Trench System, North Boundary Containment Treatment System, Rocky Mountain Arsenal, Commerce City, Colorado

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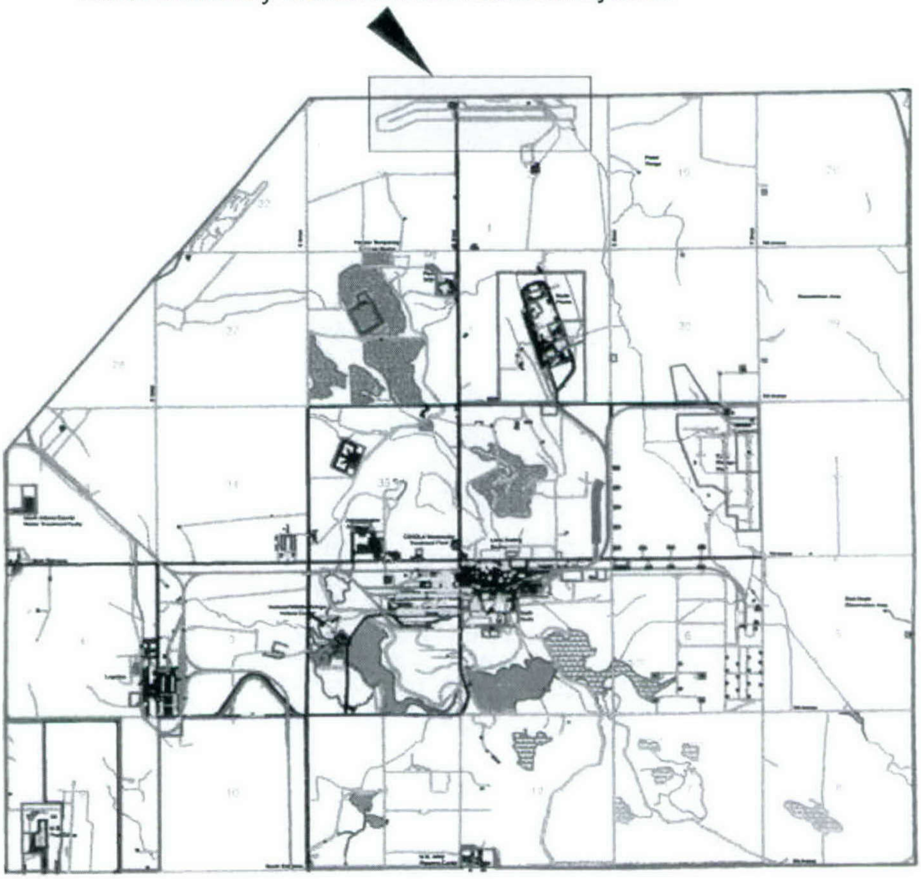
January 2005



Rocky Mountain Arsenal

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Final report

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ABSTRACT: This report summarizes hydrogeologic investigations completed in 2002 on the recharge trenches at the North Boundary Containment Treatment System (NBCTS) at Rocky Mountain Arsenal (RMA), located in Commerce City, CO. The NBCTS is a 6,740-ft (2,054-m)-long multicomponent system that precludes off-site movement of contaminated water at the north boundary of RMA. It consists of a slurry wall, dewatering wells, treatment plant, and recharge trenches.

Prior to 1988, treated water was recharged back to the shallow unconfined aquifer by means of recharge wells. Over time, these wells lost their efficiency as the result of microbial fouling, and 15 recharge trenches were constructed along the length of the system to replace the recharge wells. To address concern regarding the continued hydraulic efficiency of the system, methodologies were developed to evaluate, on a year-to-year basis, trench hydraulic conductivity. Initially, hydraulic conductivity was determined on individual trenches and trench sets according to Darcy's Law using averaged values of recharge and hydraulic gradient, as available in annual assessment reports.

In 1992, field testing was initiated, which consisted of cessation of recharge to a given trench and measurement of the decline or water levels in the trenches with time. These tests were modeled after field slug tests, and the resulting drawdown rates, which were proportional to hydraulic conductivity, were considered to provide relative information on changes in trench condition with time.

In 1996, testing was again revised, and the earlier methods were reestablished except that water levels were measured in the field and recharge (now a known quantity) was held constant during the water level reading. Having established steady-state conditions, hydraulic conductivity could be calculated for each trench on the basis of Darcy's Law. After 8 years of testing (including all methods), test results were remarkably uniform. Hydraulic conductivity calculations (averaged and real time) were determined to be within an order magnitude, as were drawdown rates. On the basis of hydraulic conductivity values, the trenches are performing similarly to well-sorted sands or well-sorted gravels.

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Conversion Factors, Non-SI to SI Units of Measurement

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
feet per hour	0.008446	centimeters per second
inches	2.541	centimeters
miles	1.609347	kilometers

Preface

This work was performed from 1992 through 2002 at the U.S. Army Engineer Research and Development Center, Waterways Experiment Station (ERDC), Vicksburg, MS, and at Rocky Mountain Arsenal (RMA), Commerce City, CO. The work was conducted under the authority of the Program Manager's Office, RMA.

The work and report preparation were performed by Ms. Maureen K. Corcoran and Dr. James H. May, Engineering Geology and Geophysics Branch (EGGB), Geosciences and Structures Division (GSD), ERDC Geotechnical and Structures Laboratory (GSL); Dr. David M. Patrick, Department of Geology, The University of Southern Mississippi (USM), Hattiesburg, MS; and Mr. Neville G. Gaggiani, U.S. Geological Survey, Commerce City, CO. Dr. May was Project Manager. General supervision was provided by Dr. Lillian D. Wakeley, Chief, EGGB; Dr. Robert Hall, Chief, GSD; and Dr. David W. Pittman, Director, GSL. The program manager at RMA was Mr. Tom James, and the ERDC project coordinator was Ms. Beth Fleming, Environmental Laboratory, ERDC.

The authors acknowledge the contributions of Mr. Colin McAneny (EGGB, retired), who developed the procedures for and conducted the first 2 years of falling-head testing at RMA. Field studies and instrumentation support were provided by Messrs. Lester R. Flowers (GSL) and Richard W. Burrow (Information Technology Laboratory), ERDC, and Mr. Clint Roberts and Ms. Beronica Lee (USM). RMA personnel and contractor employees also are thanked for their cooperation and support.

COL James R. Rowan, EN, was Commander and Executive Director of ERDC, and Dr. James R. Houston was Director.

1 Introduction

Purpose and Scope

This report describes specific hydrogeologic investigations conducted on the recharge trenches at the North Boundary Containment Treatment System (NBCTS) at Rocky Mountain Arsenal (RMA). RMA is located in Commerce City, CO, approximately 10 miles northeast of downtown Denver, CO. A location map is provided as Figure 1.

The overall purposes of conducting recharge trenches tests are to

a. Measure and evaluate hydraulic conductivity of individual trenches over time.

b. Evaluate performance of the recharge trenches.

c. Determine impact of the trenches on system efficiency.

The objectives of this report were to

a. Provide an overview of the NBCTS geology and geohydrology.

b. Document trench investigations and methodologies.

c. Present and evaluate data collected through fiscal year (FY) 2002.

Background

RMA began operations in 1942 to manufacture munitions for use in World War II. Activities at the arsenal included the manufacture and treatment of chemical, biological, and incendiary munitions and the demilitarization of chemical munitions. In 1946, Shell Chemical Company leased a portion of RMA to produce industrial chemicals and pesticides. Groundwater contamination was first noticed in the mid-1950s when minor crop damage was discovered on private land north and northwest of the arsenal. In 1974, contaminants were detected in surface and subsurface waters outside the boundary of RMA and, in April 1975,

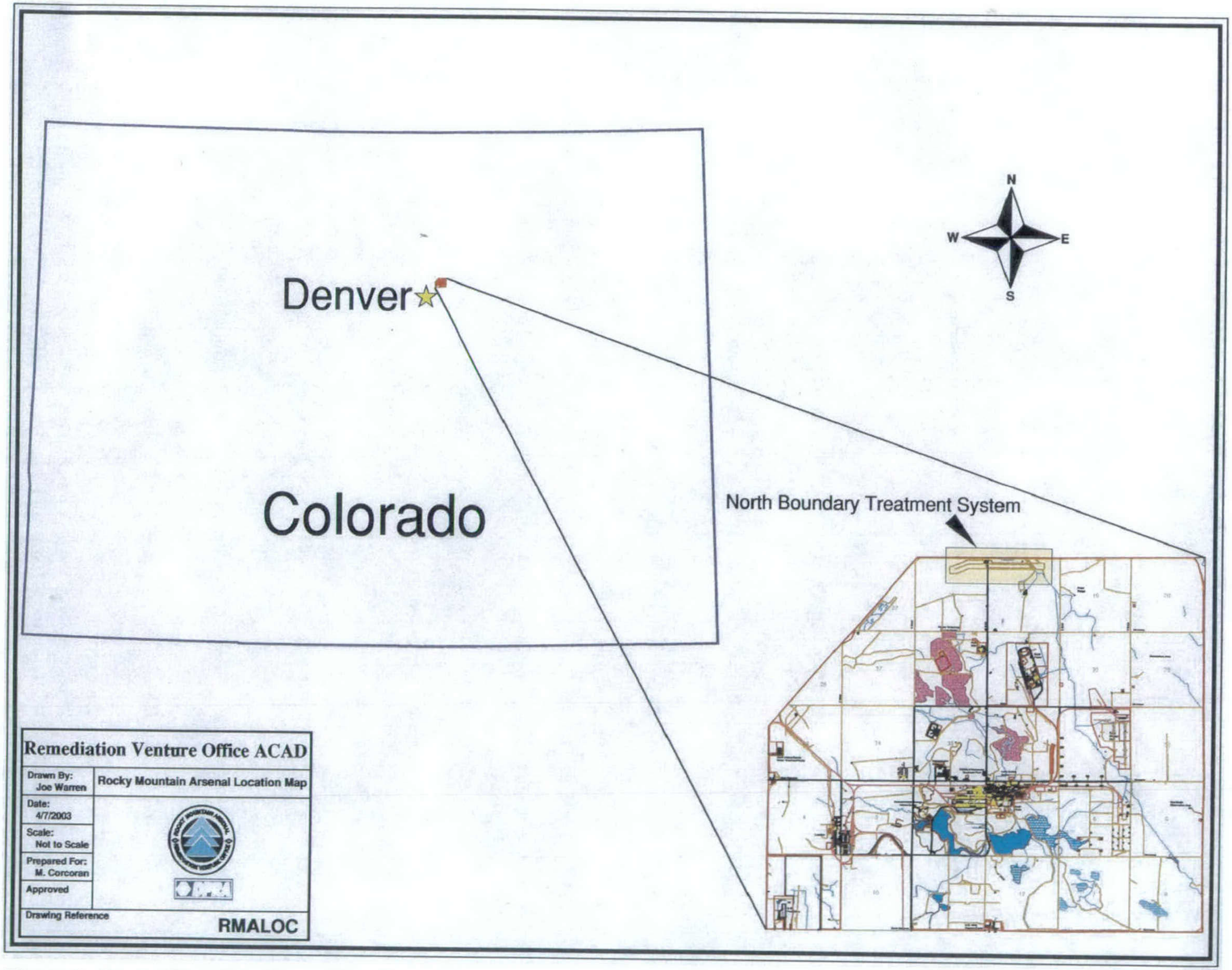

Figure 1. Rocky Mountain Arsenal location map

the Colorado State Department of Health issued Cease and Desist Orders to Shell Chemical Company and RMA (May 1982).

In 1977, the NBCTS was designed as a pilot study to test the effectiveness of a pump-and-treat system at RMA. In 1988, the NBCTS was expanded to its current length and operational level. The system is designed to prevent offsite migration of northward-flowing contaminated water in the shallow, upper aquifer. It currently extends 6,470 ft,[1] east to west, along the northern boundary of RMA. The original containment system consisted of a 3-ft-wide and 30-ft-deep bentonite slurry wall barrier keyed into shale of the Denver Formation; 34 extraction or dewatering wells located along and 250 ft south and upgradient from the barrier; a carbon-absorber treatment plant to treat the extracted water; and, as originally designed and operated (1978 through 1988), 37 injection or recharge wells along and 250 ft north and downgradient from the barrier to return the treated water to the upper aquifer. During the early 1980s, well recharge became increasingly ineffective in part due to low permeability of upper aquifer materials and to microbial fouling of the recharge wells themselves. Therefore, beginning in 1988, the original system design was modified to replace the recharge wells with 15 recharge trenches to more effectively return treated water to the upper aquifer. Figure 2 is the system configuration of the NBCTS, as of November 2002.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page v.

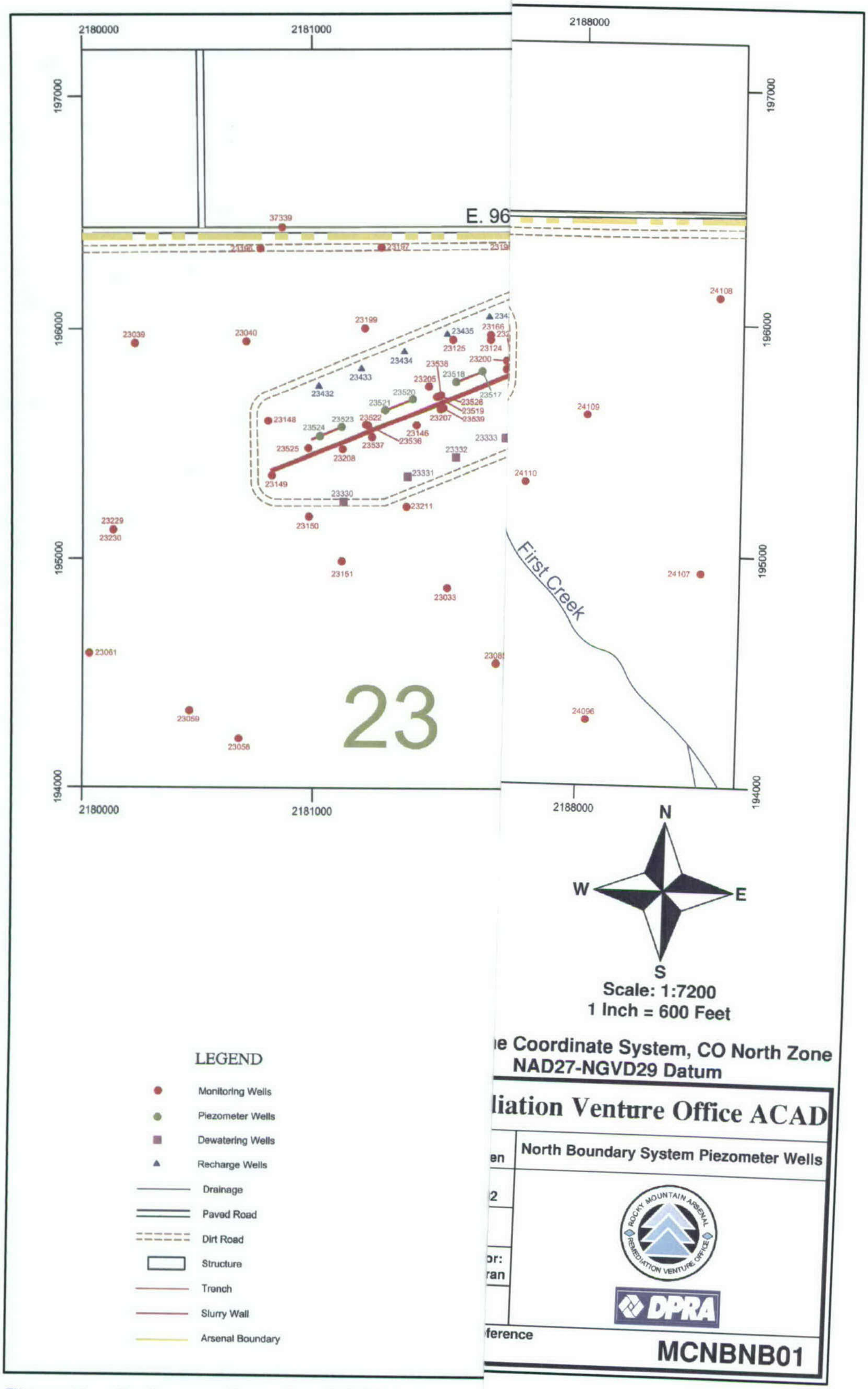

Figure 2. System configuration, NBCTS, Novem

2 Geologic and Geohydrologic Setting

NBCTS Geology

Stratigraphic relations between two geologic units control near-surface groundwater systems at RMA and effectiveness of the recharge trenches and slurry wall barrier: the older Cretaceous Denver Formation and the overlying Quaternary deposits. The Denver Formation consists of 250 to 300 ft of heterogeneous interbedded clay shale, claystone, siltstone, and sandstone conformably overlying the Arapaho Formation (Morrison-Knudsen Engineers, Inc. 1988).[1] Figure 3 shows a west-east geologic cross section parallel to the barrier and demonstrates that, although there are significant shaley or clayey facies in the unit, there are also a number of sandy or sandstone facies as well. The deeper sandy and, therefore, more permeable facies of the Denver Formation are relevant in areas where these sandy facies are in contact with the Quaternary alluvium.

The erosional paleosurface of the Denver Formation, which developed during the Pleistocene, reflects the erosional history of the South Platte River valley. At RMA, this surface is characterized by numerous Pleistocene paleochannels, three of which have been identified in the vicinity of the barrier. The materials in the paleochannels consist of several feet of poorly cemented siltstone and sandstone lenses. Overlying the Denver Formation and paleochannel materials (if present) is a fining-upward sequence of well-sorted sand and gravel overlain by approximately 15 ft of silt and clay. This sequence has been described as the Slocum Alluvium (ESE 1989) and is glaciofluvial in origin resulting from glacial melting in the Rocky Mountains to the west. This unit mantles most of RMA and has been reworked during the Holocene. Locally, eolian silts are present at the surface.

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[1] See also J. H. May et al. (1980), "Hydrologic assessment of Denver sands along north boundary of Rocky Mountain Arsenal." Geotechnical Laboratory, Vicksburg, MS.

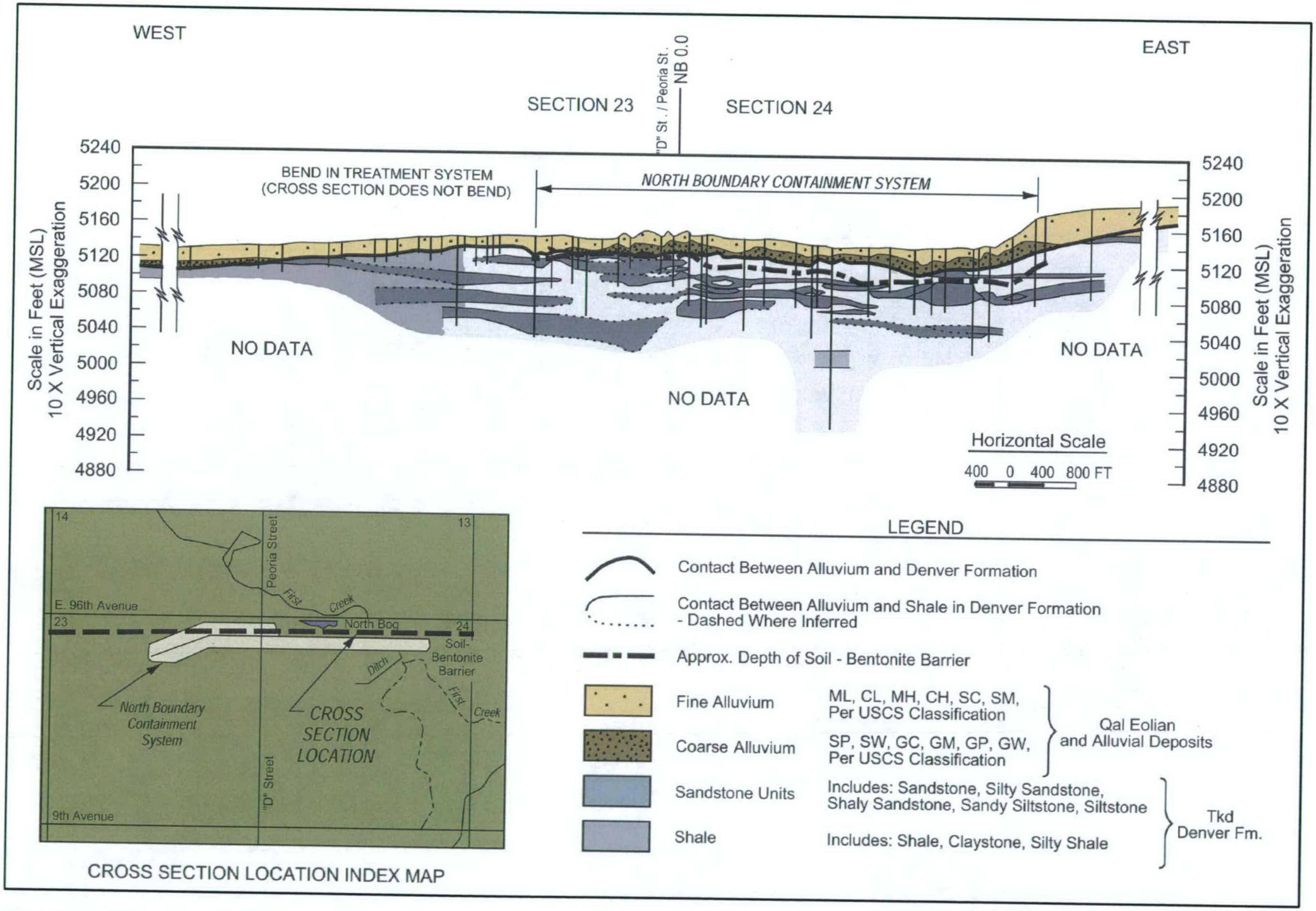

Figure 3. East-west geologic cross section along the NBCTS slurry wall (ESE 1989)

NBCTS Groundwater Flow Systems

Two groundwater flow systems are important to the operation of the NBCTS: a confined aquifer in the deeper Denver sandstone and siltstone lenses and an upper, generally unconfined aquifer.

Confined aquifer

Sandstone and siltstone lenses occur in the Denver Formation at various depths and locations along the barrier and the isolated deeper ones comprise the confined aquifer. Annual hydrographs show parallel changes in pressure heads in both confined and unconfined aquifers, implying that both aquifers are controlled by seasonal precipitation. Because of their depths beneath the barrier, these lenses are not relevant to this study.

Unconfined aquifer

The Slocum Alluvium is the principal sediment body of the unconfined aquifer. The slurry wall extends through this alluvium and is keyed in the clayey facies of the Denver Formation. Locally, however, the Slocum Alluvium overlies a paleochannel and/or sandstone or siltstone lenses of the Denver Formation. Where these conditions occur, the slurry wall extends down through the lenses. The Denver lenses and the paleochannel materials are included with the Slocum Alluvium as part of the unconfined aquifer. Comparisons of annual hydrographs from wells screened in the Slocum Alluvium, paleochannel materials, and Denver lenses, have shown sufficiently similar pressure heads and are, therefore, considered to be hydraulically interconnected (May 1982; May et al. 1980, 1983).

Results of numerous pumping tests have shown that hydraulic conductivities of both systems are highly variable as expected from the heterogeneous nature of the aquifer materials. Potentiometric surface maps included in annual assessments have shown that the direction of groundwater flow in both aquifers is to the north and flow in the upper aquifer is controlled by a north-south aligned paleochannel (Lutton 1989). These maps also indicate the highly variable hydraulic conductivity of the upper aquifer by the steepness of the potentiometric surface in the vicinity of the western end of the barrier where a steep bedrock surface and low-permeability aquifer materials coincide (Environmental Engineering Division (EED) 1996, 1995; Environmental Science and Engineering, Inc. (ESE) 1989; Technical Operations Division (TOD) 1990, 1991, 1996, 1997).

3 Recharge Trenches

Recharge Well Fouling

Difficulty in maintaining effective recharge increased during the studies of the injection wells initiated in the 1980s. These investigations included excavation of a selected well and laboratory analysis of the screen, gravel pack, and aquifer material. Analyses indicated activated carbon fines were present in the recharge well screen and gravel and that these fines were contributing to microbial growth in the wells. The combination of carbon fines and microorganisms was blocking pore space, thereby decreasing the hydraulic conductivity of the wells, which, in turn, was reducing the effectiveness of the overall system.[1] Because of their greater cross-sectional area and higher recharge rates, recharge trenches were considered to be an acceptable alternative to wells from several standpoints including less likelihood of fouling, greater interface, and communication with the aquifer.

Recharge Trench Implementation

In 1988, ten recharge trenches (T1-T10) were constructed along the western half of and downgradient from the barrier. The major deviation from the conceptual design was to increase the length from 100 ft to approximately 160 ft to allow an eastern extension of the trench line. During FY90, five additional trenches (T11-T15), with lengths of approximately 400 ft each, were added along the eastern half and downgradient from the barrier, completing the trench system. The trenches average 15 ft in depth and were designed to penetrate at least 3 ft into the unconfined aquifer with recharge water entering a perforated plastic pipe situated longitudinally near the top of the gravel interval (Figure 4). An impermeable membrane separates the top of the gravel from the backfill material, thereby preventing intrusion of surrounding sediment. The recharge trenches are placed approximately 45 ft from the slurry wall, closer than the recharge wells, to maximize the high water-table position north of the barrier. Piezometers were installed near the ends of the trenches and between trenches in order to assess trench performance and to monitor groundwater conditions. Shorter trenches, those placed at 100-ft intervals, conceptually proved more advantageous based on convenience of replacement, control of recharge, and localized shutdown.

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[1] G. D. Comes. (1993). "Fouling of Recharge Well No. 413 at the Rocky Mountain Arsenal," M.S. thesis (unpublished), Mississippi State University, Starkville, MS.

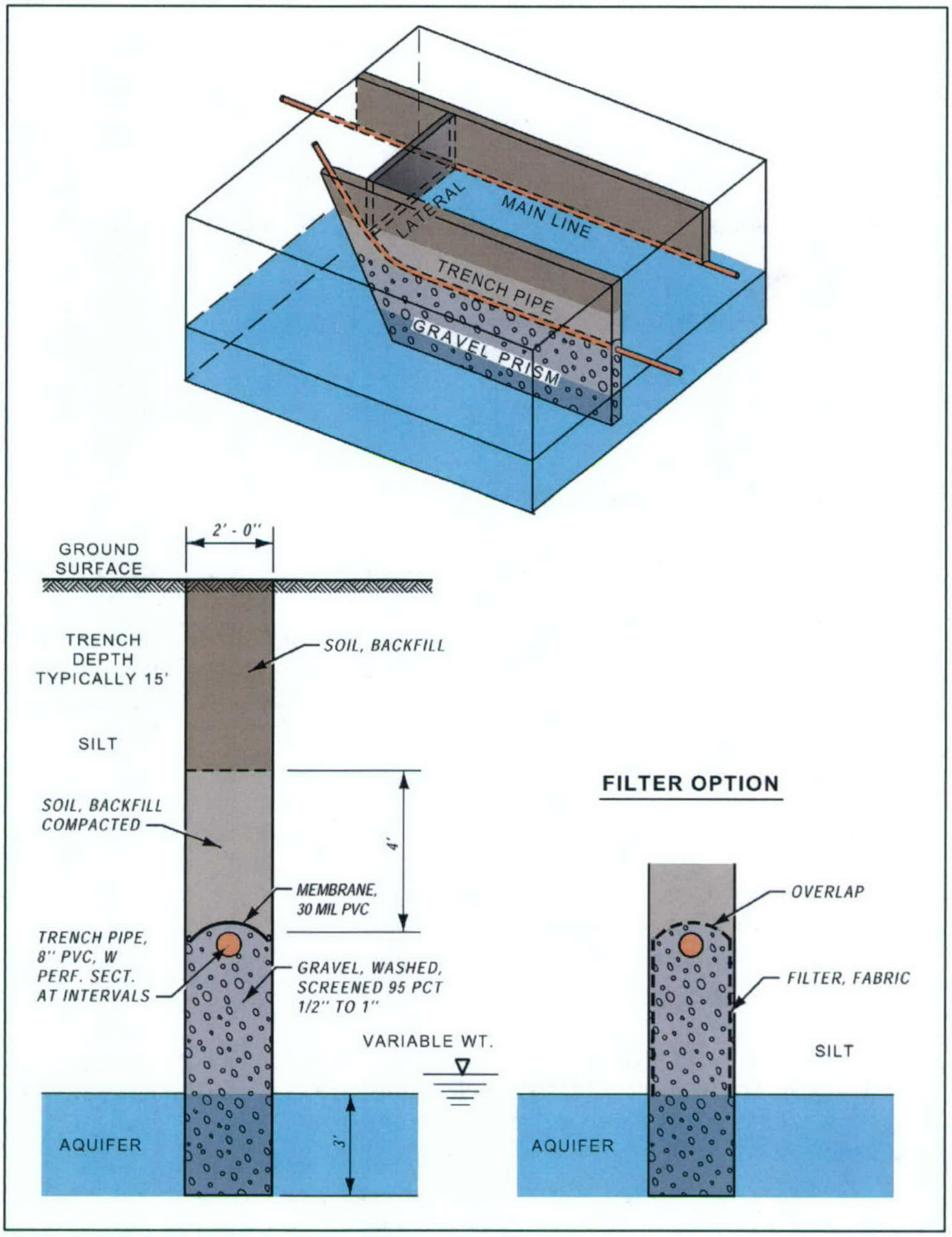

Figure 4. Deep-gravel trench design detail (Lutton 1988)

Trench locations were determined based on data from existing dewatering, recharging, and monitoring wells; however, knowledge of NBCTS geology was increased substantially by data collected from monitoring wells installed during the construction phases of trench implementation (Lutton 1988).

4 Evaluation and Testing Methodology

Start-Up Evaluations

In 1989, Lutton described the design and start-up performance of the first 10 trenches. In his report, he proposed and demonstrated a method for providing information relative to the hydraulic conductivity of the trenches. He assumed that equilibrium was established, steady-state conditions prevailed and, because the water levels were in a steady state, Darcy's Law could be applied as follows:

$$K = Q / Ai \qquad (1)$$

where

K = hydraulic conductivity of trench/aquifer system
Q = water discharge into the trench
A = cross-sectional area of the trench through which Q flows
i = hydraulic gradient

In this method, Q values were averages obtained from RMA treatment plant operations; the area, A, was the trench length multiplied by average depth; and the hydraulic gradient, i, was determined from monitoring well data within and downgradient from the trench. Over the next several years, the annual operational assessments of the NBCTS included similar calculations of hydraulic conductivity with minor changes in the method of obtaining Q and i. For example, in FY92, the hydraulic gradient was calculated for the fourth quarter, and Q was determined from the average discharge for a given trench for that quarter. The hydraulic gradient was that gradient for a given trench or trenches indicated on the potentiometric surface map prepared for that quarter. Usually, because of the scale and contour interval of the potentiometric surface map, calculations were conducted on a set of two or more trenches to determine a more accurate hydraulic gradient. Also, because Q-values were averages and the i-values did not necessarily correspond to specific values of Q, the calculated values of K were, at best, approximations. Even so, these data taken as a whole appeared to be useful and provided insight to the effectiveness of the trenches (ESE 1989; EED 1995, 1996; TOD 1991, 1996, 1997).

Falling Head Tests

Realizing the need for a more accurate and real-time method for evaluating trench performance, a procedure was initiated in 1992 and extended through 1995 designed after the falling- or variable-head laboratory test used on fine-grained soils (Lambe and Whitman 1969) and based upon the conditions and principles of the slug test used in the field (Freeze and Cherry 1979, Fetter 2001). A slug test is generally used in small-diameter wells when the hydraulic conductivity is too low to conduct a pumping test. Water is either added to the well casing or withdrawn by bailing out (bail-down) the casing with a special tool called a bailer (Fetter 2001). This trench test used the Hvorslev slug test method, which usually determines hydraulic conductivity of the formation in which a screen or gravel pack is located.

Although mathematically dissimilar, these relations show that the hydraulic conductivity is proportional to a change in head over time as shown in Equation 2 below:

$$K = dh/dt \tag{2}$$

Thus, this proportionality states that trench hydraulic conductivity is proportional to the rate of change in head after recharge to the trench ceases. Therefore, after the cessation of recharge to a trench, plots of drawdown (water level) versus time could be used to compare relative changes in hydraulic conductivity for that trench from quarter to quarter or from year to year. A basic assumption in this method is that the recharge, q, did not exhibit significant variation from one testing period to another. This is an important assumption because recharge is also proportional to hydraulic conductivity (Equation 2). Even so, experience has shown that recharge variations at RMA are normally less than an order of magnitude.

Because one of the major limitations in bail-down testing is the requirement for a high-quality piezometer intake, reduced hydraulic conductivity can be used as an indicator of fouling. However, water surging prior to testing, which is a possibility when the system is shut down, can result in higher than normal conductivities, which greatly decreases the value of using hydraulic conductivities as trench-performance indicators.

From 1992 to 1995, recharge trenches 4, 5, 6, 9, 10, and 11 were evaluated. Trenches were tested in groups of three, for example, 4, 5, 6, and 9, 10, and 11 using special instrumentation over two 24-hr periods during the spring or summer months and required approximately 5 field days.

The testing procedure described by McAneny[1] consisted of

a. Instrumenting the trench wells by using pressure transducers, data loggers, and signal cables with computer download capability.

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[1] C. C. McAneny. (1993). "Falling head tests in recharge trenches, North Boundary Containment System, Rocky Mountain Arsenal," Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dataloggers were set to record at certain intervals to produce an exponential decline in the water level.

b. Measuring water levels in nearby monitoring wells upon installation of instrumentation, recharge to all trenches being tested was cut off for 24 hr and declines in water level measured.

c. Downloading drawdown data to a computer and plotting water elevation versus time.

McAneny stated that an attempt to quantitatively calculate previous piezometer readings did not appear fruitful. McAneny based this statement on the plots of water elevation versus time. The plots indicate that the Hvorslev method should not be considered as an accurate representation of a localized hydraulic conductivity but rather as a generalized account of water-level decline.

The initial trench test was designed as a baseline to serve as a comparison for future tests conducted under the same method. Unfortunately, the plots of water-level decline did not always behave according to the same type of tests conducted in vertical wells. Because the falling head test and slug test (bail-down method) are based on wells and not trenches, reasonable hydraulic conductivities could not be determined from this testing method. The test did indicate which trenches are more effective based on comparisons between the trenches but did not consider trench configuration. However, lithologic variation of the surrounding formation could also be used to determine which trenches would be in a more permeable medium and, therefore, be more effective. Although drawdown rates provided some information on trench performance, drawdown rate is also a function of recharge prior to cessation of pumping.

Revised Trench Testing

The last falling head test was conducted in 1995. In the following year, upon reviewing 4 years of data, ERDC WES developed a new procedure that appears to provide more accurate measurement of hydraulic conductivity. This method is similar to that used by Lutton in his early attempts to monitor trench condition except that real-time water level and recharge data are collected for each trench. The procedure consists of the following steps:

a. Determine the value and consistency of recharge to each trench to ensure that the recharge is not changing before or during the test.

b. Measure the water levels in the trench and in downgradient monitoring wells.

c. Calculate hydraulic conductivity of each trench using the following formula, which is an expanded form of Equation 1:

$$Q = \left[\frac{K(h_1 - h_2)(h_1 + h_2)}{2d} \right] L \qquad (3)$$

where

Q = discharge through trench-aquifer system
K = hydraulic conductivity of the trench aquifer system
h^1 = difference between water elevation in downgradient monitoring well and Denver Formation well
h^2 = difference between average water elevation in trench and Denver Formation water elevation
d = distance between trench and downgradient monitoring well
L = length of recharge trench

This equation was developed by Dupuit (Fetter 2001). Its development and application are based upon the following assumptions:

a. The aquifer is in steady state and exhibits a relatively flat gradient.

b. The trenches are narrow linear features having widths that are small compared to their length, which results in relatively uniform flow normal to the long axis of the trench.

c. There is negligible flow through the ends of the trench and only minor interference between trenches.

d. Flow is only to the north with ponding between the trench and the slurry wall.

e. The availability of suitably located downgradient monitoring wells.

Figure 5 is a plan view showing a generalization of a trench and a downgradient monitoring well used in calculating the hydraulic conductivity. The distance between a trench and monitoring well (*l*) varies with availability of suitable downgradient wells. Water levels in both trench piezometers were measured, and the average was used in the calculation. Figure 6 is a north/south cross section of the trench configuration used in the revised trench test.

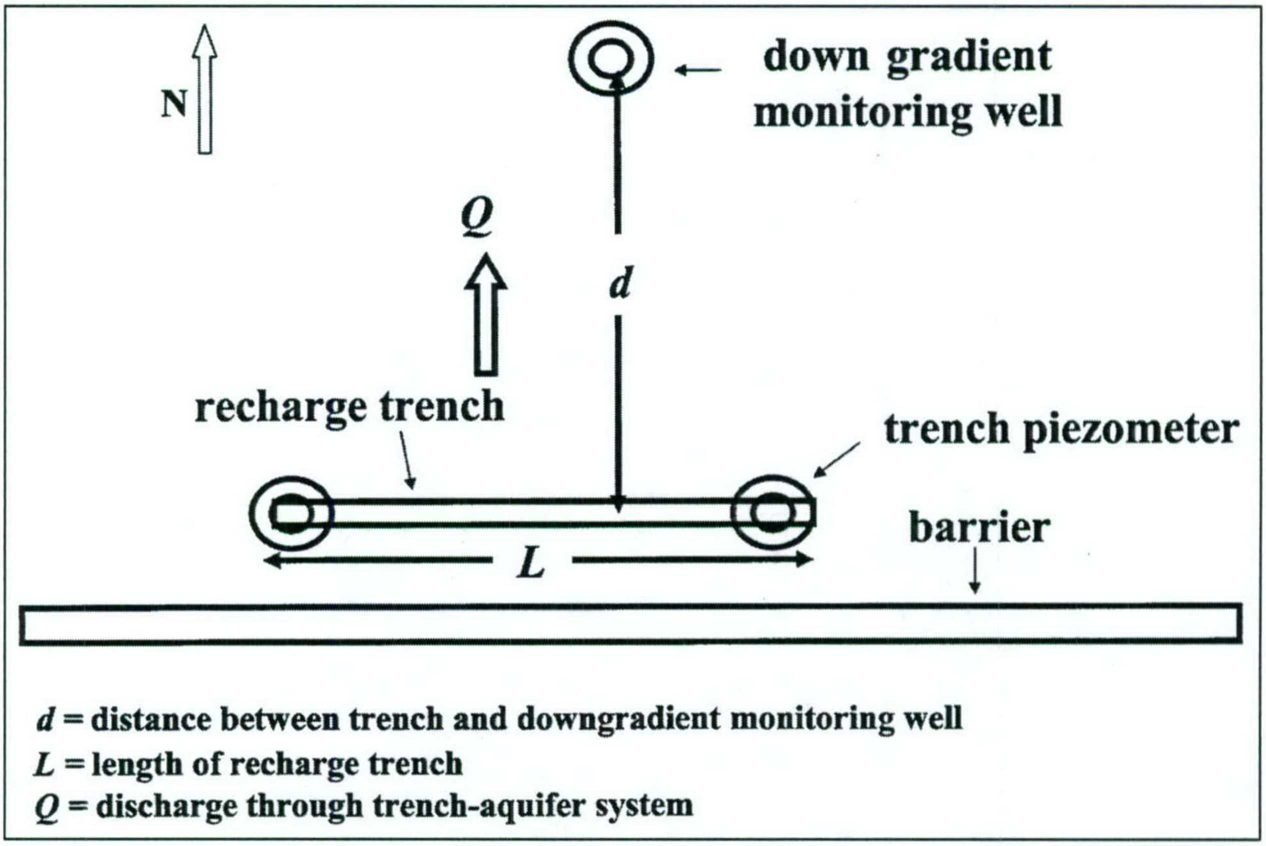

Figure 5. Plan view (north/south) of the configuration for the revised trench test

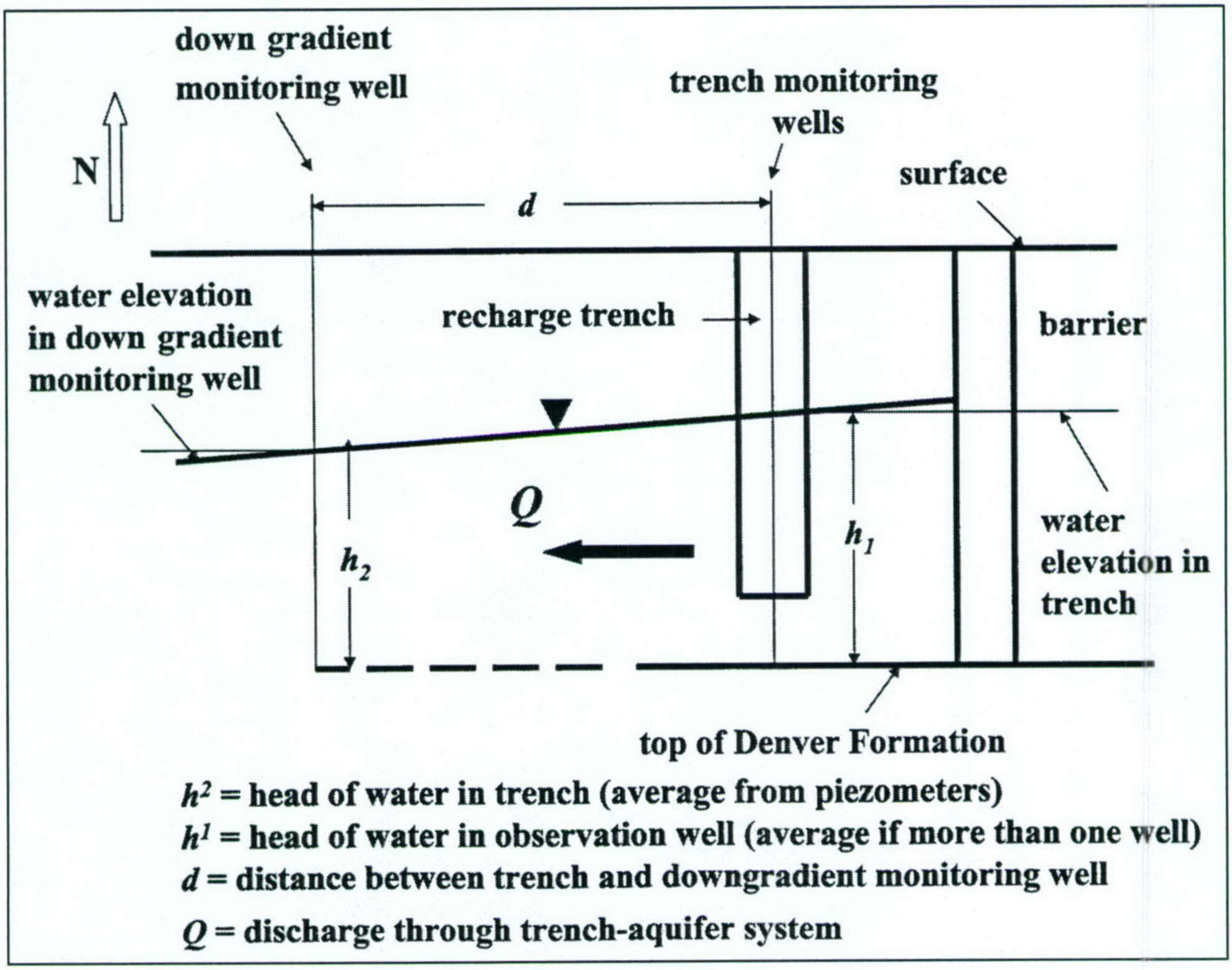

Figure 6. Cross section (north/south) of the configuration for the revised trench test

5 Results

Start-Up Test Results

During Lutton's early work (1989), only trenches 4 through 10 had steady-state conditions and therefore, were suitable for testing. Using Equation 2, described in the last section, a hydraulic-conductivity (*K*) value of 0.0464 cm/s was calculated for the seven-trench system (Table 1). This value is comparable to *K* for clean, medium-coarse sand. In 1978, several pumping tests were conducted approximately 2,000 ft south of the trenches, and hydraulic-conductivity values calculated from these tests ranged from 0.053 to 0.13 cm/s. These pumping test values tend to support the meaningfulness of the trench evaluations. Later annual evaluations based on modification of Lutton's method are shown in Table 1 for FYs 1990, 1991, and 1992. In 1990, hydraulic conductivity was calculated for adjacent trench sets. However, in 1991 and 1992, calculations were made for individual trenches. Generally, year-to-year data for a given trench appeared reasonable for coarse materials, and the values were all within an order of magnitude. The data also show more significant variability between trenches. Note that these types of calculations were not conducted during FYs 1993 through 1996.

Falling Head Test Results

Plots of drawdown versus time for the 4 years of testing are presented in Appendix A. Testing was conducted from east to west along the trench line. In most cases, piezometers in each end of the trench were monitored; thus, there are usually two plots for each trench. Two- and three-channel data loggers were used at different times during this 4-year period. When the three-channel model was used, channels 1 and 2 monitored Trench 4, for example, and the third channel monitored the eastern piezometer in Trench 5. This resulted in piezometer drawdowns for a given trench being plotted on different graphs. In some instances, monitoring was conducted prior to trench recharge shutdown and at other times, monitoring commenced with the shutdown. The occasional spikes seen on the drawdown plots are caused by radio transmission interference from or to the NBCTS treatment plant.

Table 1 **Recharge Trench Hydraulic-Conductivity Values (cm/s)**								
Trench/FY	**FY89**	**FY90**	**FY91**	**FY92**	**10/96**	**06/97**	**09/98**	**07/02**
1	[1]	0.003	0.16	0.000048	[1]	[1]	[1]	0.0055
2	[1]		[1]	[1]	[1]	[1]	[1]	0.0092
3	[1]		0.03	0.021	[1]	[1]	[1]	0.025
4	0.0464		0.006	0.026	0.01	0.0295	0.020	0.026
5		0.011	0.025	0.027	[1]	0.0238	0.038	0.013
6			0.12	0.090	0.111	0.173	0.25	0.19
7		0.045	0.24	0.210	0.245	0.168	[1]	0.24
8			0.076	0.028	[1]	0.383	0.35	0.20
9			0.058	0.081	[1]	0.0485	0.01	0.0042
10			0.018	0.037	0.053	0.0736	0.69	0.045
11	[2]	0.034	0.037	0.049	0.375	0.619	0.43	0.36
12	[2]		0.015	0.023	[1]	[1]	[1]	0.033
13	[2]		0.024	0.160	0.095	0.111	0.25	0.13
14	[2]	0.014	0.018	0.084	1.59	2.054	0.25	0.069
15	[2]		0.009	0.076	[1]	[1]	[1]	0.028

[1] Hydraulic conductivity not determined/no recharge.
[2] Trenches not yet constructed.

Examination of the plots in Appendix A indicates that drawdown, in most cases, was relatively slow, and the rate of drawdown did not change appreciably from the start to the conclusion of testing. Because hydraulic conductivity is proportional to the rate of drawdown, drawdown rates were calculated for the first 2 hr of testing. The 2-hr period is arbitrary. Drawdown units are given in feet per hour for simplicity of presentation. These rates are shown in Table 2. For each trench and year, the value on the left is the eastern piezometer; the west piezometer is on the right.

Table 2 **Initial Drawdown Rates (*dh/dt*) (ft/hr) After 2 Hours of Testing**								
Trench/Year	**1992**		**1993**		**1994**		**1995**	
4	0.065	0.065	0.12	ND[1]	0.18	0.17	0.016	0.02
5	0.13	0.135	0.0015	0.0015	0.20	0.21	0.41	0.35
6	0.455	0.41	0.40	0.41	0.40	0.43	0.41	0.41
9	0.186	0	0.005	ND	0.015	0.13	0.075	ND
10	0.275	0.275	0.37	0.37	0.33	0.28	0.12	0.12
11	0.16	0.07	0.14	0.12	0.075	0.06	0.09	0.02

[1] No data collected.

These data, for the most part, indicate that drawdown rates were similar at both ends of the trenches, and overall rates were also similar from year to year. Trench 6 exhibits the least variability and Trenches 5 and 9, the greatest variability. Generally, most of the data are within an order of magnitude. Although hydraulic conductivity cannot be calculated directly based on these data, one may conclude that there appear to be no significant changes in the hydraulic condition of these trenches during this 4-year period. Examination of the plots in Appendix A also shows that water levels within a number of trenches differed by as much as 3 ft from one end of the trench to the other. Therefore, there must have been a component of flow through and along the long axis of the trenches during drawdown. The long-axis flow indicates that nonunidirectional flow

probably has interfered with drawdown, and that system equilibration over a period of time would contribute to better test results.

Revised Trench Test Results

The first revised trench test was conducted at RMA on 1 October 1996 (FY97). Field conditions were favorable, and only 2 man-days were needed to complete tests on 15 trenches. Plans were coordinated with Technical Operations to ensure that recharge remained constant and the system remained in a steady state. Printouts were obtained throughout the test days to verify system recharge, and these recharge values were used in the calculations. Water levels were measured for all wells during the first day and were repeated for verification on the second day. Trenches 1, 2, and 3 were dry and, therefore, excluded from further analysis. Figure 2 identifies wells measured with an M-scope, an electrical water level-sensing device, during the test. Trench piezometers are noted as green circles, and monitoring wells used in the calculations are shown as red circles. The trenches were tested in a similar manner on 11 and 12 June 1997 (FY98). The hydraulic-conductivity values are given in Table 1.

Reproducibility of these data is apparent in that the data from the second day of testing were, in most cases, nearly identical to those of the first day for 1996 and 1997. Comparing 1997 to 1998, there was more variability in the data; however, the variation was within an order of magnitude. The hydraulic-conductivity data generally conform to the values calculated during start-up and shortly thereafter (FY89 to 92). Differences between the hydraulic-conductivity values of different trenches are apparent.

6 Discussion and Data Analysis

Trench – Aquifer System

Collection, calculation, and analysis of data relative to the permeability or hydraulic conductivity of earth materials, whether conducted in the laboratory or from pumping tests in the field, pose a number of challenges relevant to the analysis and evaluation of the trenches. Use of these data to detect changes in the condition of in situ materials is an additional challenge. In a field pumping test, one of the most informative but most expensive methods, the formation is tested over some distance from the well with hopes of sampling a sufficient volume of formation to provide meaningful data. The well screen and gravel pack represent a small volume relative to the formation, and one assumes that these components have sufficiently high hydraulic conductivity so they do not impede the passage of water to the well. However, fouling may interfere with both screen and packing. With respect to the recharge trenches, the situation is somewhat different from the pumping test in that the gravel in the trenches is the material of interest. In reality, data collected in the field, regardless of test type, are those of a two-component system consisting of the trench gravel and the formation (unconfined aquifer).

Data Variability

Test data have shown a degree of variability in hydraulic conductivity from trench to trench. The variability may be due to differences in the lithology of the unconfined aquifer rather than the trenches themselves, because they consist of gravel. From comparison of these data with typical hydraulic-conductivity values given by Fetter (2001) and presented in Table 3, one would consider the test data to be similar to that of well-sorted sands or gravels.

The degree of variability from year to year and from trench to trench may be seen in Table 4, which groups the start-up and revised test data by order of magnitude. This arrangement of the data shows that, for the most part, hydraulic-conductivity values are those of well-sorted sands and gravels as previously indicated. The number of trenches is too small to extract any meaningful statistical data; however, note that the grouping of the values appears to have a "normal-

type" distribution (two-tailed) and to be skewed toward the lower hydraulic-conductivity values.

Table 3
Typical Hydraulic-Conductivity Values (cm/s) for Non-Lithified Materials (after Fetter 2001)

Well-sorted gravel	10^{-2} - 1
Well sorted sands	10^{-3} - 10^{-1}
Silty and fine sands	10^{-5} - 10^{-3}
Silt, sandy silt, clayey sand	10^{-6} - 10^{-4}
Clay	10^{-9} - 10^{-6}

Table 4
Variation in Trench Hydraulic-Conductivity Values (cm/s) by Year

Fiscal Year	Number of Trenches Having Hydraulic-Conductivity Values			
	10^{-1} or greater	10^{-2}	10^{-3} or less	No. Tested
1991	3	9	2	14
1992	2	11	1	14
1996	4	3	0	7
1997	6	4	0	10
1998	6	3	0	9
2002	5	7	3	15

Domenico and Schwartz (1990) presented a relevant discussion of the variability of hydraulic-conductivity values for a given formation. Typically, these values exhibit a log-normal distribution as opposed to a normal one, and the skewness is toward the high hydraulic-conductivity side. The trench data do not have this type of distribution. Thus, one may surmise that the formation (unconfined aquifer) is not playing a major controlling role in the hydraulic-conductivity test although the variation that is seen is probably formation related.

Examination of the data in Table 1 also shows some year-to-year variation; however, comparison of data for FY91 and FY92 shows that most values are within an order of magnitude. The FY97 and FY98 revised test data also are quite similar; however, they are somewhat larger than the values calculated for FY91 and FY92 during and after start-up.

Sources of Error or Variation

Sources of errors or causes of variability in the data are a function of how the test was run and how the data were calculated. Difficulties and inaccuracies associated with the start-up and falling-head methods already have been discussed. In this section, inaccuracies with the revised test will be addressed. A very positive outcome of the revised trench tests was the very close similarity between tests conducted on successive days in October 1996 and June 1997. These data are tabulated in Table 5. These data support the reproducibility of the methodology and the requirement that the system was in or close to a steady state. Although there were differences in water levels within the trenches during drawdown test-

ing, this was not the case during the revised tests. The small variations seen from 1996 to 1997, and those between successive days, however, may indicate that the system had not quite equilibrated and reached a true steady state. For example, where differences were observed, the recharge, q, also was different, indicating that small changes of recharge may affect the hydraulic-conductivity values. Also, the locations of the monitoring wells may not be the most conducive for determining the hydraulic gradients along the flow path north of the trenches.

Table 5
Comparison of Successive Day Hydraulic-Conductivity Values (cm/s)

Trench/Date	1996		1997	
	1 October	2 October	11 June	12 June
4	ND	ND	0.0295	0.029
5	ND	ND	0.0238	0.023
6	0.144	0.111	0.173	0.173
7	ND	0.245	0.168	ND
8	ND	ND	0.383	0.381
9	ND	ND	0.0485	0.046
10	0.053	0.053	0.0736	0.074
11	0.375	0.378	0.619	0.619
13	0.095	0.096	0.111	0.112
14	1.591	1.592	2.054	ND

Significance of Data

Previous discussion and analysis have shown that the revised trench test method is a rapid, inexpensive, and relatively accurate means of collecting hydraulic-conductivity values that are reproducible and that appear meaningful. Research should continue, however, to refine and further develop analytical methods for assessment of trench effectiveness. Hydraulic-conductivity values aid in identifying the hydraulic-conductivity variability of the unconfined aquifer along the NBCTS. Trenches 4 and 5, 9 and 10, and 15 appear to exhibit lower values probably because of poorer sorting or the presence of finer sediment (i.e., silt) in the unconfined aquifer in these areas. The highest hydraulic-conductivity value occurs at Trench 14 and is most likely related to the presence of coarser and better sorted materials in the nearby paleochannel.

The relations noted above are interesting and useful; however, the significance of the data in terms of trench condition also must be addressed. Generally, based on the data in Table 1, there is an overall increase in hydraulic conductivity from 1989 through 1997. This increase is most likely meaningless and merely reflects differences between the start-up versus the revised test methodologies. Small differences in recharge were evident during the last 2 years of testing. Thus, the present data do not provide any information with regard to changes in trench condition. The data do indicate that the trench-system performance has been and is similar to that of a well-sorted sand or well-sorted gravel and, therefore, is efficient and satisfactory.

7 Conclusions and Recommendations

Conclusions

a. The trench-aquifer system consists of the upper aquifer and the 15 trenches.

b. Recharge trench testing at RMA has been an ongoing and evolutionary process.

c. The current, revised trench testing has improved the ability to provide real-time, rapid, inexpensive, and reproducible hydraulic-conductivity data.

d. These data have shown that the trenches that were tested are operating efficiently and, based on the hydraulic-conductivity data, behaving as well-sorted sand or gravel bodies.

e. Those trenches having somewhat lower values of hydraulic conductivity most likely are situated in parts of the unconfined aquifer that are silty, clayey, or poorly sorted.

f. Based on hydraulic-conductivity and drawdown data, there is no reason to conclude that there has been any reduction in trench performance.

g. Hydraulic testing of the trenches needs to be conducted after the system has equilibrated.

Recommendations

a. Hydraulic-conductivity testing using the revised test methods should be continued on at least a semiannual basis.

b. Field personnel should continue to ensure that recharge remains as constant as possible during the test and, if practical, several hours prior to testing.

c. RMA should consider installing piezometers downgradient and centered on each trench to provide more accurate hydraulic-gradient data along the flow path.

d. RMA also should consider conducting in situ microbial testing of trenches to identify evidence of fouling.

Summary

Offsite movement of contaminated water at the northern boundary of RMA is precluded by a 6,740-ft-long multicomponent system, referred to as the North Boundary Containment Treatment System, consisting of a slurry wall, dewatering wells, treatment plant, and recharge trenches. Prior to 1988, treated water was recharged back to the shallow unconfined aquifer by means of recharge wells. Over time, these wells lost their efficiency because of microbial fouling, and 15 recharge trenches were constructed along the length of the system to replace the recharge wells. Upon construction of the trenches, there was concern for the continued hydraulic efficiency of the system, and methodologies were developed to evaluate, on a year-to-year basis, trench hydraulic conductivity. Initially, hydraulic conductivity was determined on individual trenches and trench sets according to Darcy's Law using averaged values of recharge and hydraulic gradient as available in annual assessment reports.

In 1992, field testing began, which consisted of cessation of recharge to a given trench and measurement of the decline of water levels in the trenches with time. These tests were modeled after field slug tests; the resulting drawdown rates, which were proportional to hydraulic conductivity, were considered to provide relative information on changes in trench condition with time.

In 1996, testing again was revised, and the earlier methods were reestablished except that water levels were measured in the field and recharge, now a known quantity, was held constant during the water-level reading. Having established steady-state conditions, hydraulic conductivity could be calculated for each trench on the basis of Darcy's Law. After 8 years of testing (including all methods), test results have been remarkably uniform. Hydraulic-conductivity calculations (averaged and real time) have been within an order magnitude, as were drawdown rates, and based on hydraulic-conductivity values, the trenches are performing similarly to well-sorted sands or well-sorted gravels.

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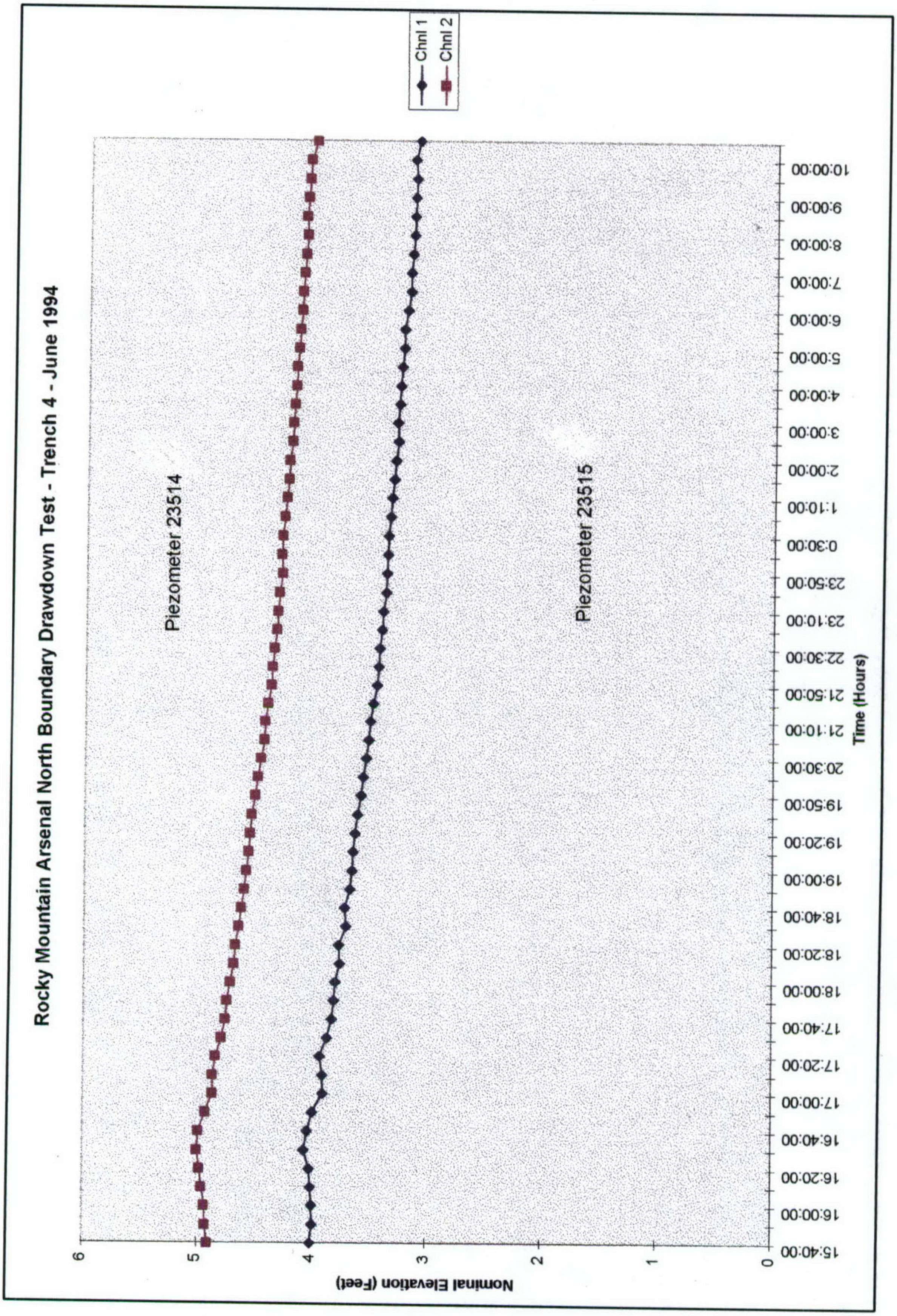
Appendix A
Drawdown Test Plots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Piezometer 23514
Piezometer 23515
Chnl 1
Chnl 2
Nominal Elevation (Feet)
0
1
2
3
4
5
6
Time (Hours)
15:40:00
16:00:00
16:20:00
16:40:00
17:00:00
17:20:00
17:40:00
18:00:00
18:20:00
18:40:00
19:00:00
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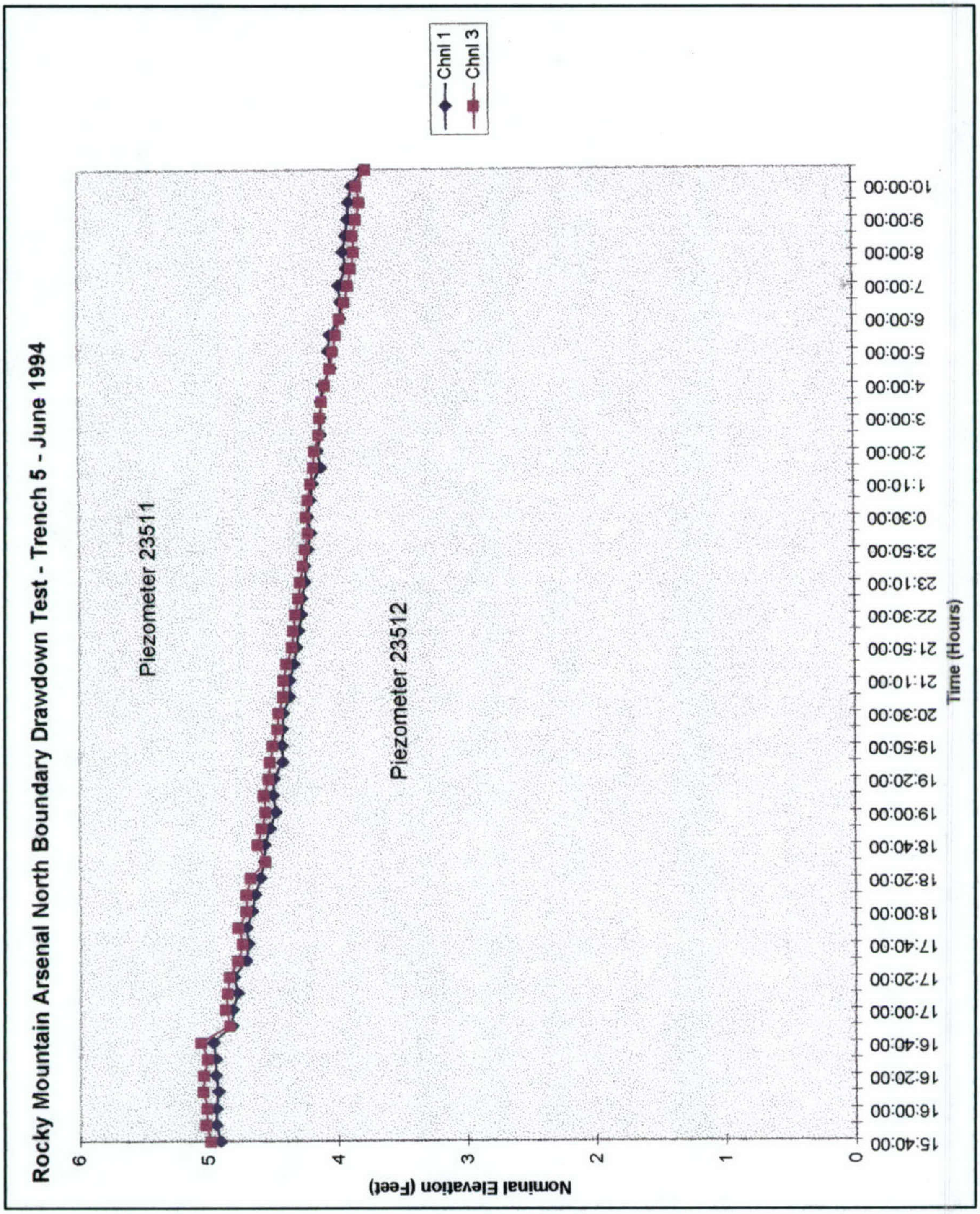
10:00:00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Piezometer 23512
Nominal Elevation (Feet)
Time (Hours)
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Chnl 3
0
1
2
3
4
5
6
15:40:00
16:00:00
16:20:00
16:40:00
17:00:00
17:20:00
17:40:00
18:00:00
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18:40:00
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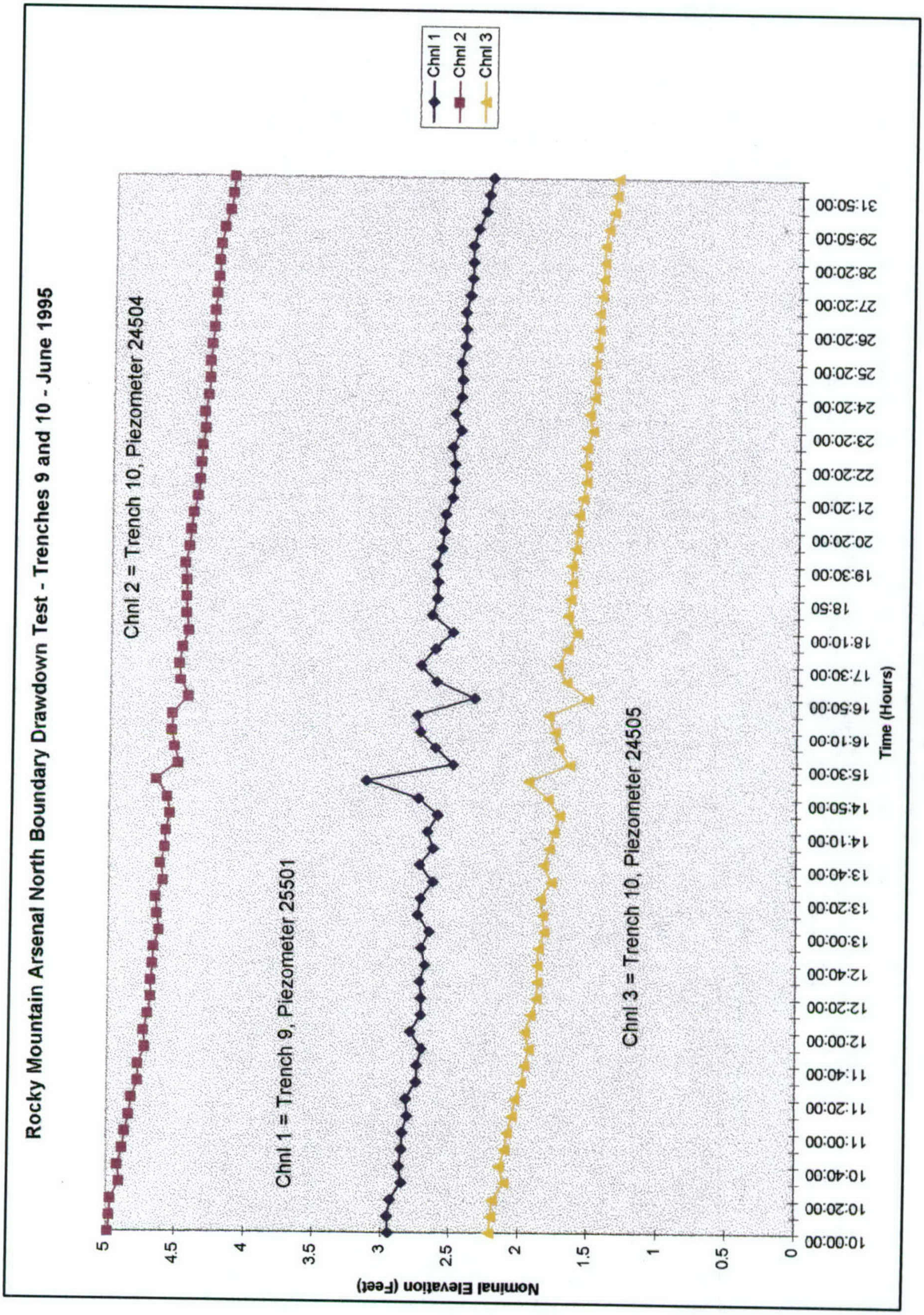
10:00:00



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Chnl 2 = Trench 10, Piezometer 24504
Chnl 3 = Trench 10, Piezometer 24505
Chnl 1
Chnl 2
Chnl 3
Nominal Elevation (Feet)
Time (Hours)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10:00:00
10:20:00
10:40:00
11:00:00
11:20:00
11:40:00
12:00:00
12:20:00
12:40:00
13:00:00
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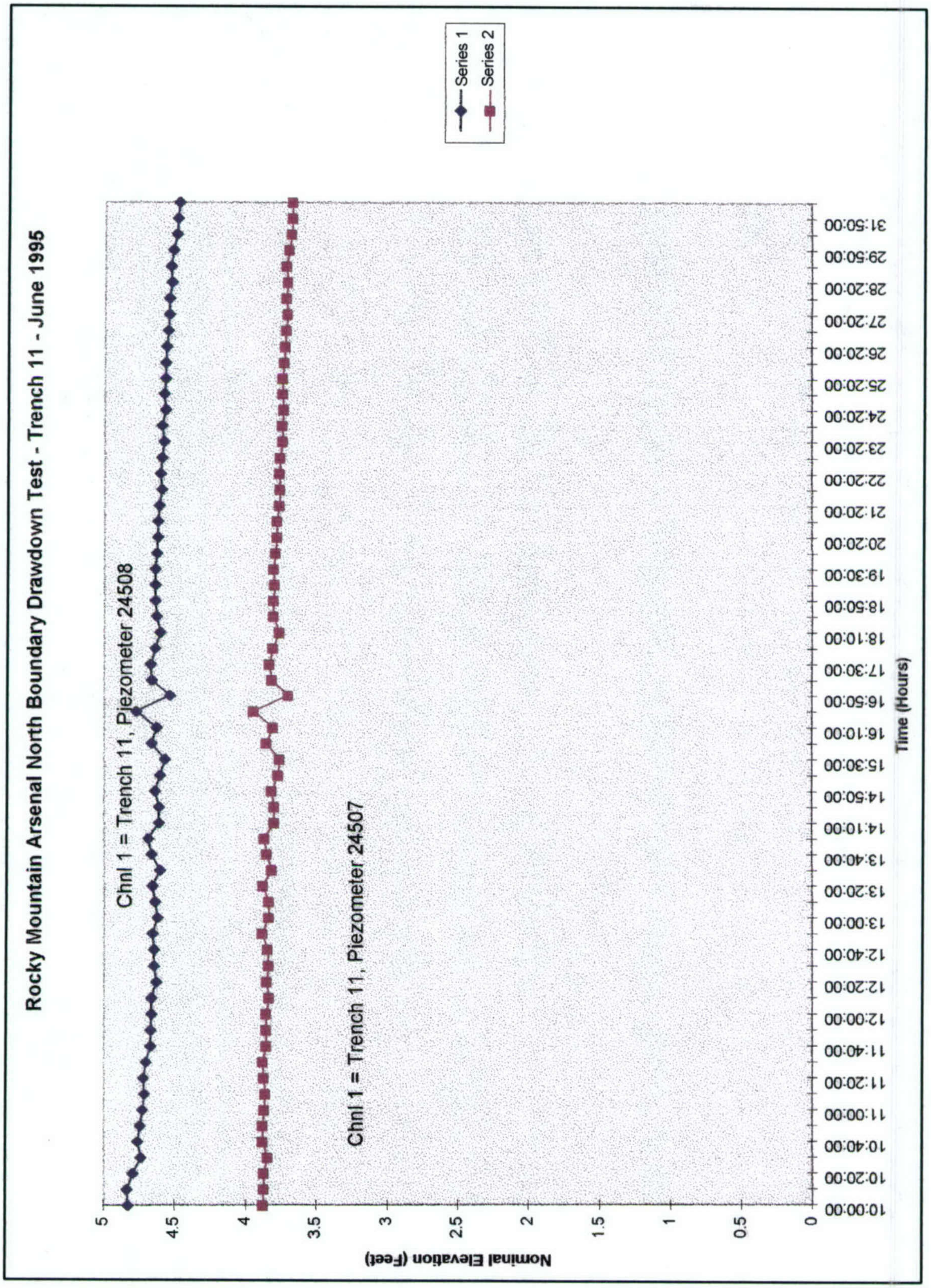
31:50:00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Chnl 1 = Trench 11, Piezometer 24507
Series 1
Series 2
Nominal Elevation (Feet)
Time (Hours)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
10:00:00
10:20:00
10:40:00
11:00:00
11:20:00
11:40:00
12:00:00
12:20:00
12:40:00
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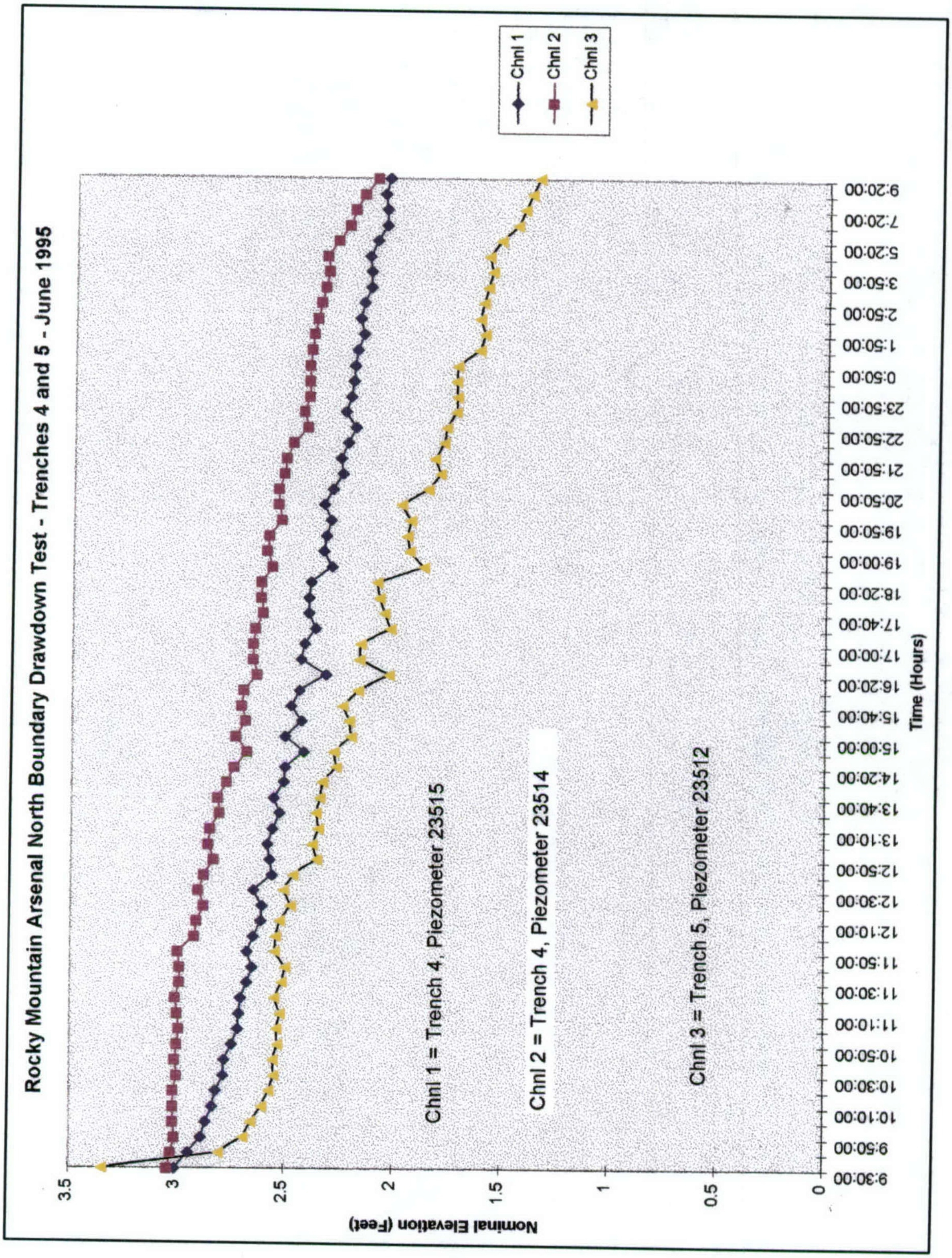

Rocky Mountain Arsenal North Boundary Drawdown Test - Trenches 4 and 5 - June 1995
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Chnl 2
Chnl 3
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Chnl 2 = Trench 4, Piezometer 23514
Chnl 3 = Trench 5, Piezometer 23512
Nominal Elevation (Feet)
Time (Hours)
3.5
3
2.5
2
1.5
1
0.5
0
9:30:00
9:50:00
10:10:00
10:30:00
10:50:00
11:10:00
11:30:00
11:50:00
12:10:00
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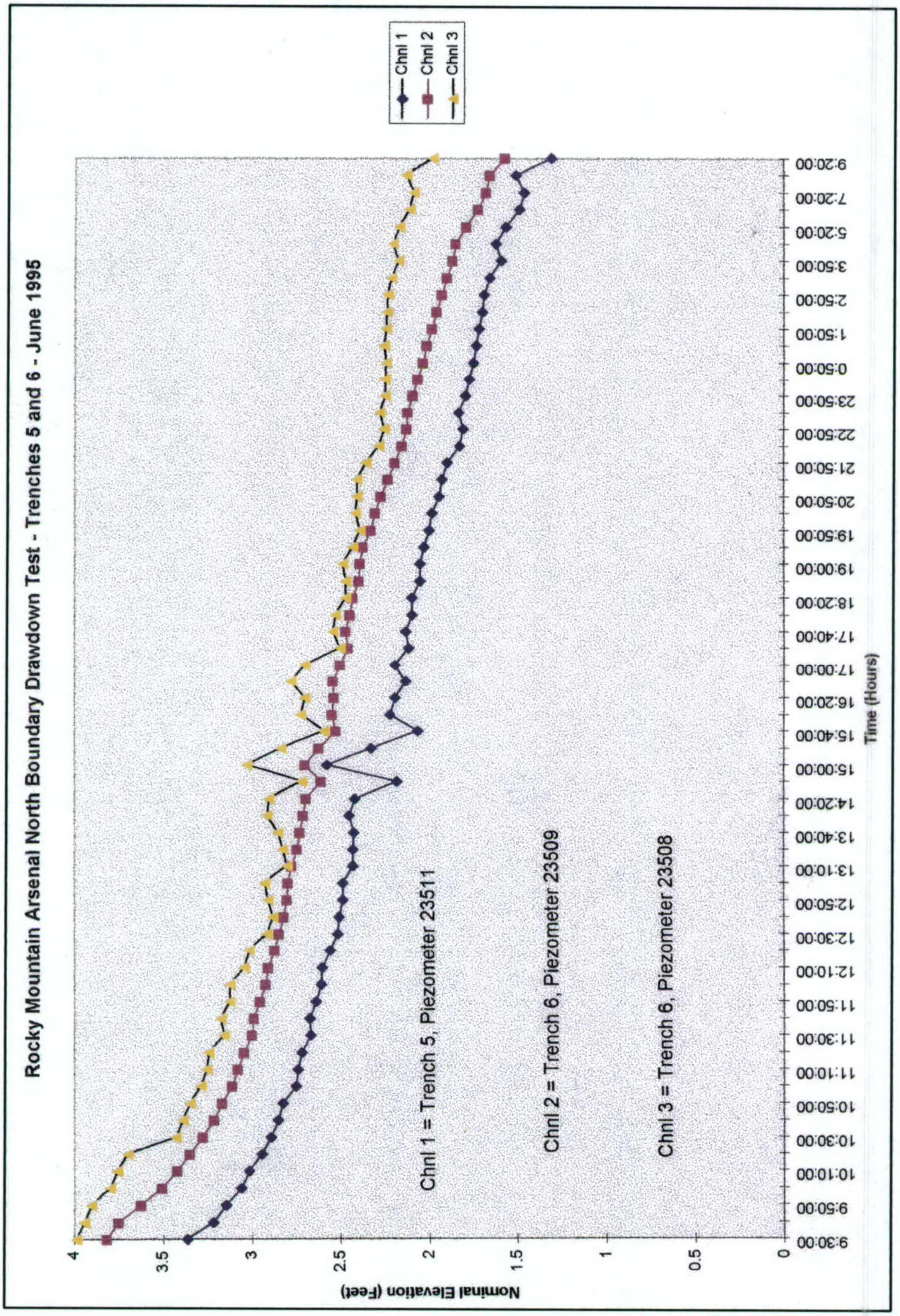
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Chnl 2
Chnl 3
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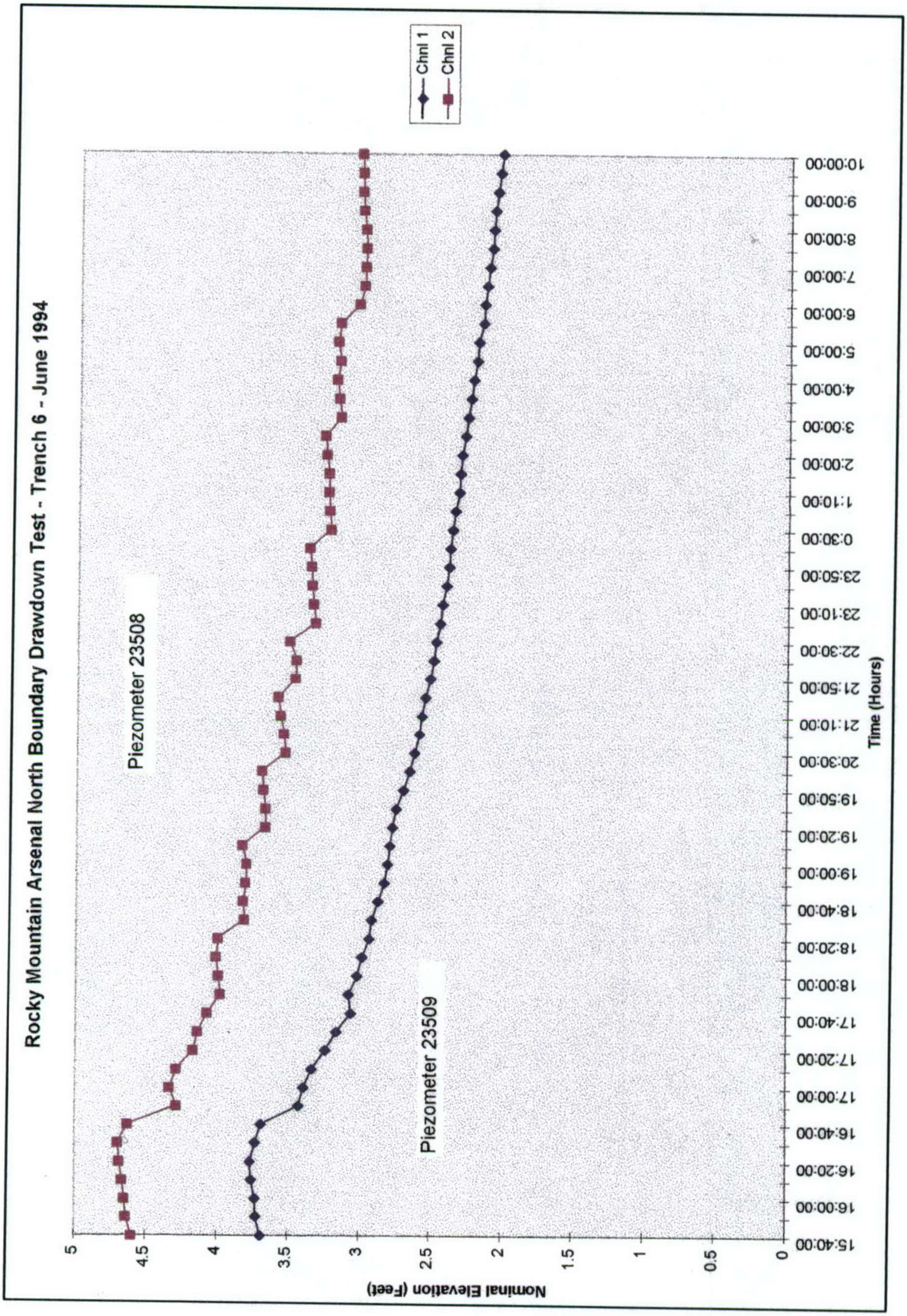
Chnl 2 = Trench 6, Piezometer 23509
Chnl 3 = Trench 6, Piezometer 23508
Nominal Elevation (Feet)
Time (Hours)



Rocky Mountain Arsenal North Boundary Drawdown Test - Trench 6 - June 1994
Chnl 1
Chnl 2
Piezometer 23508
Piezometer 23509
Nominal Elevation (Feet)
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0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (Hours)
15:40:00
16:00:00
16:20:00
16:40:00
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17:40:00
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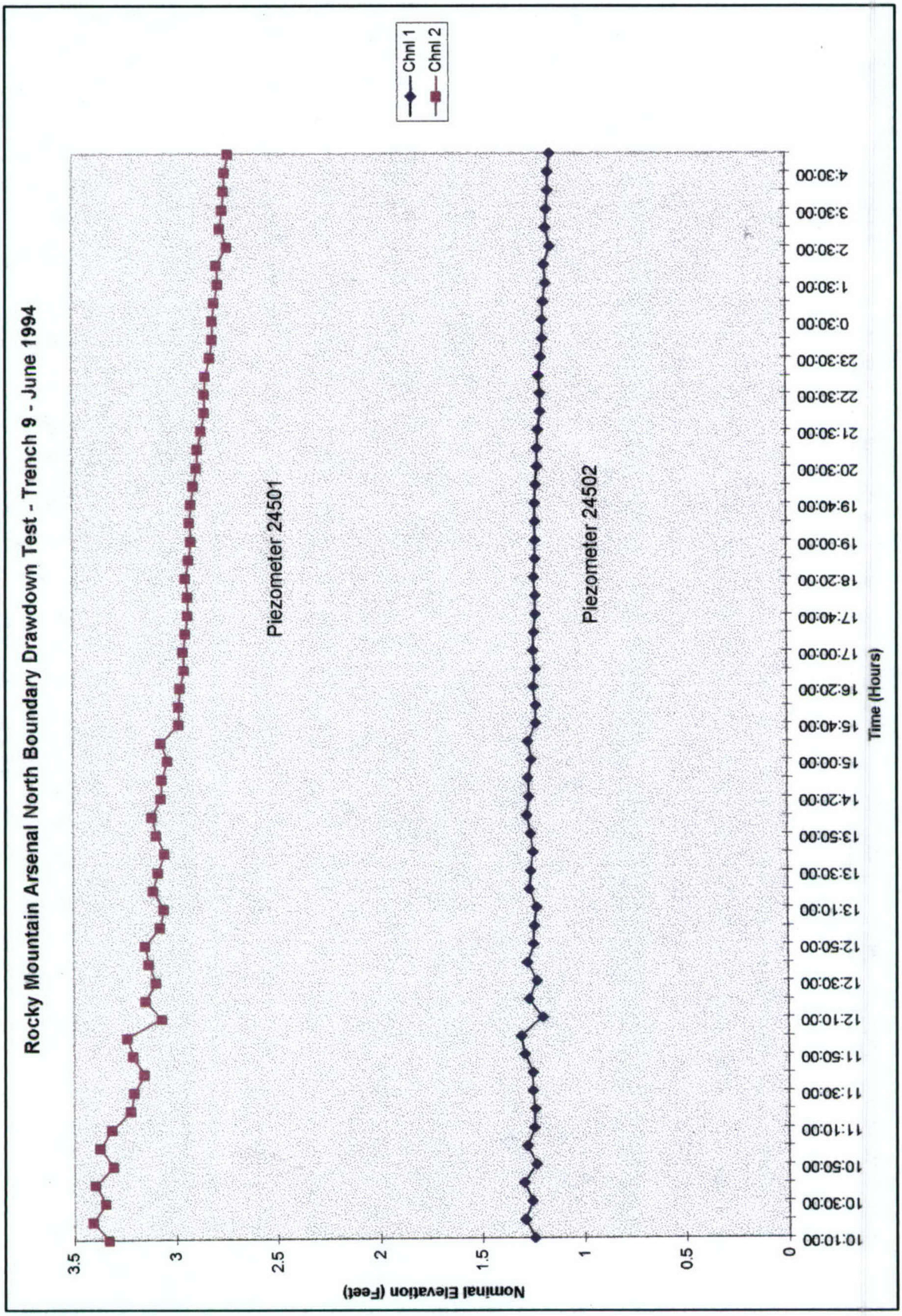
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Chnl 1
Chnl 2
Piezometer 24501
Piezometer 24502
Nominal Elevation (Feet)
Time (Hours)
3.5
3
2.5
2
1.5
1
0.5
0
10:10:00
10:30:00
10:50:00
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11:50:00
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12:50:00
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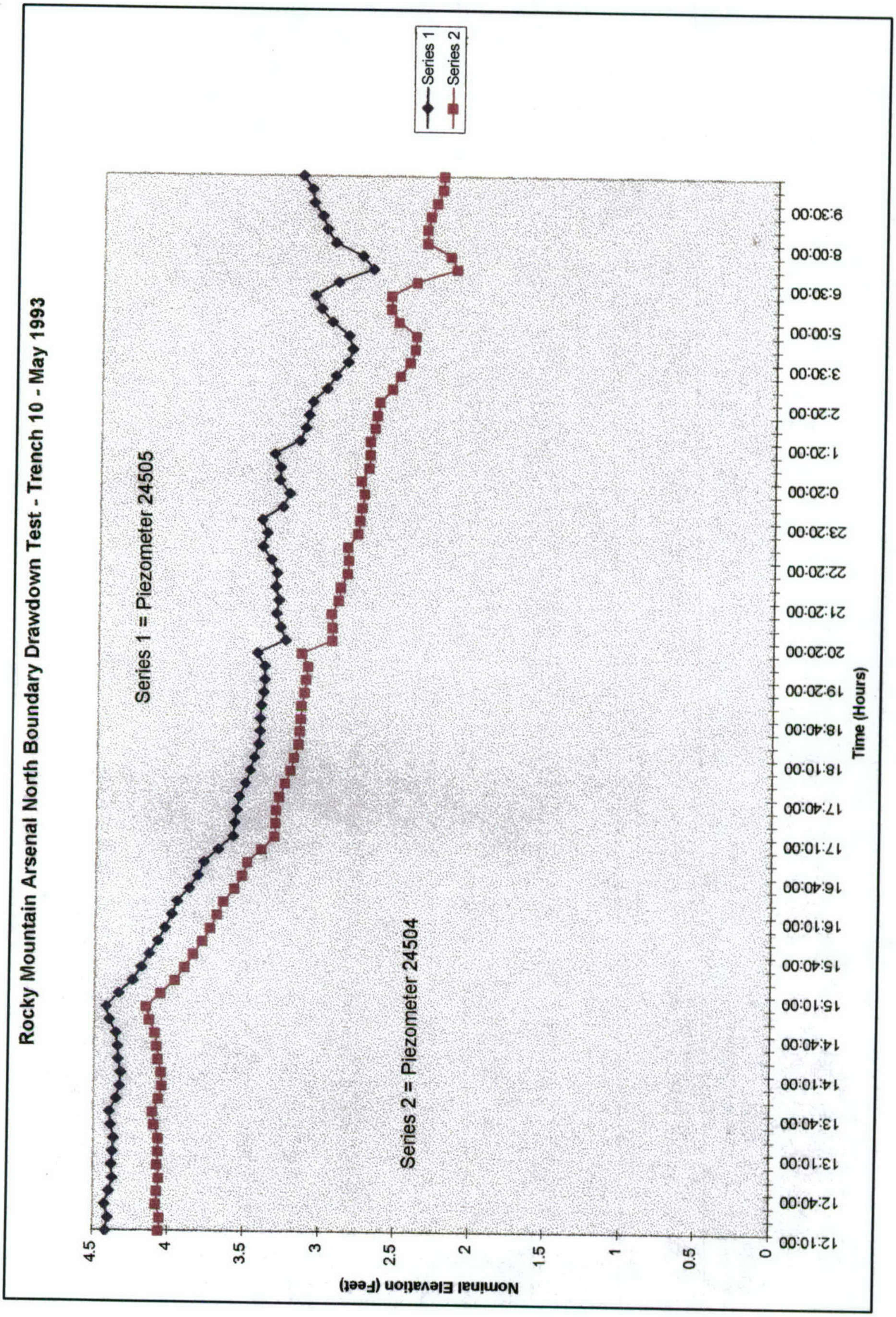
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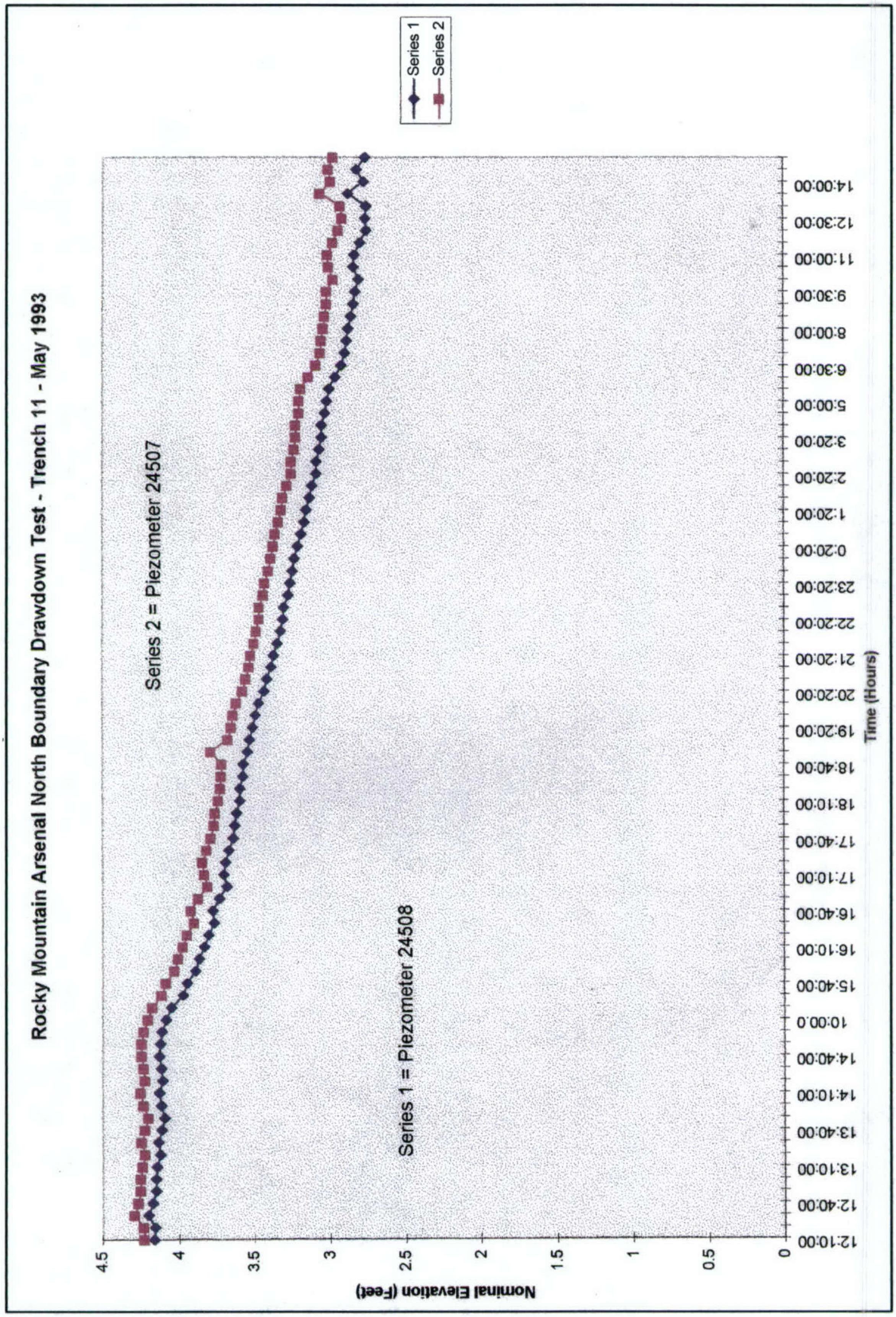
Series 1
Series 2
Nominal Elevation (Feet)
Time (Hours)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Nominal Elevation (Feet)
Time (Hours)
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Series 2
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2
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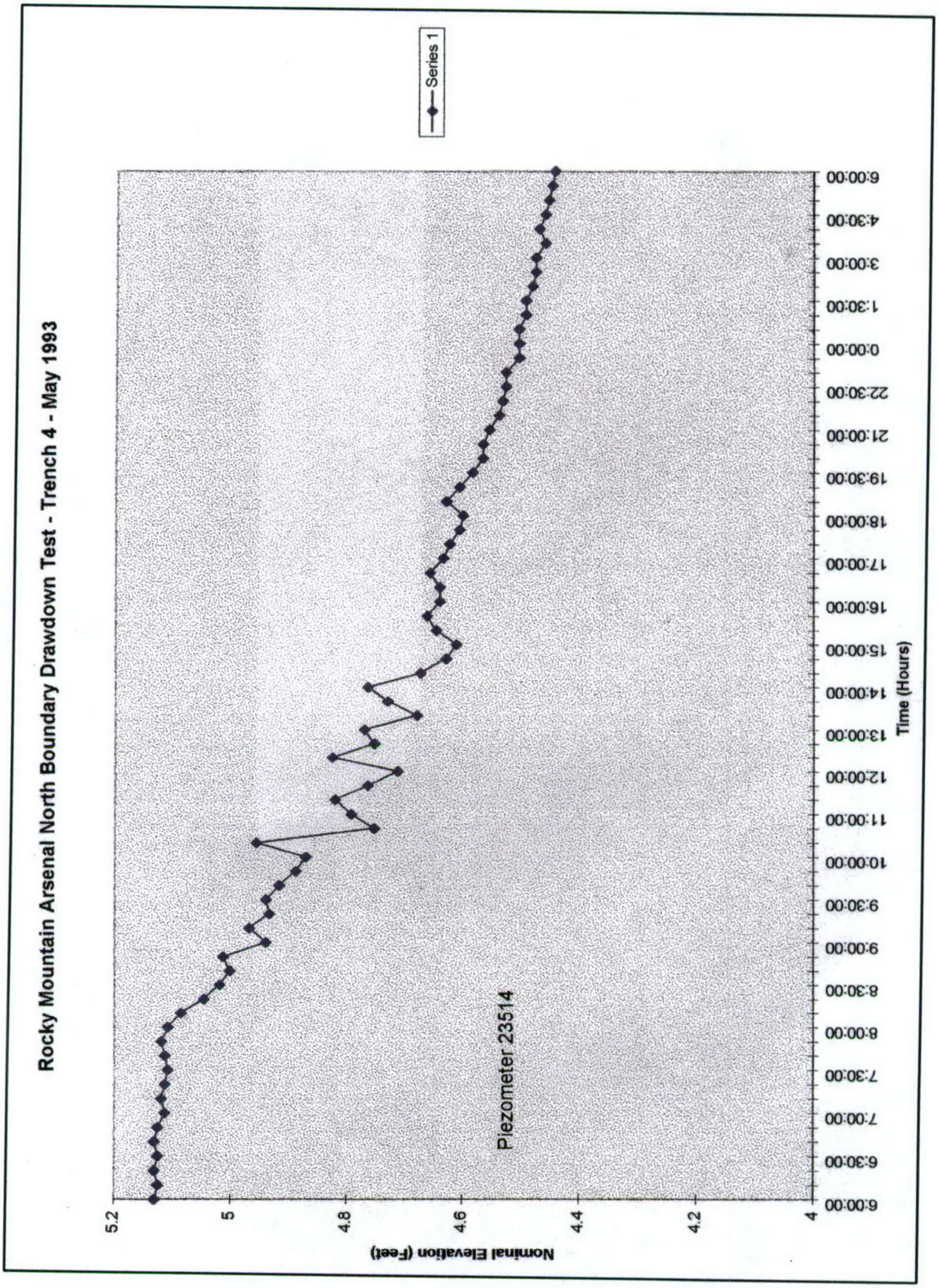
3
3.5
4
4.5



Rocky Mountain Arsenal North Boundary Drawdown Test - Trench 4 - May 1993
Nominal Elevation (Feet)
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5
4.8
4.6
4.4
4.2
4
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19:30:00
21:00:00
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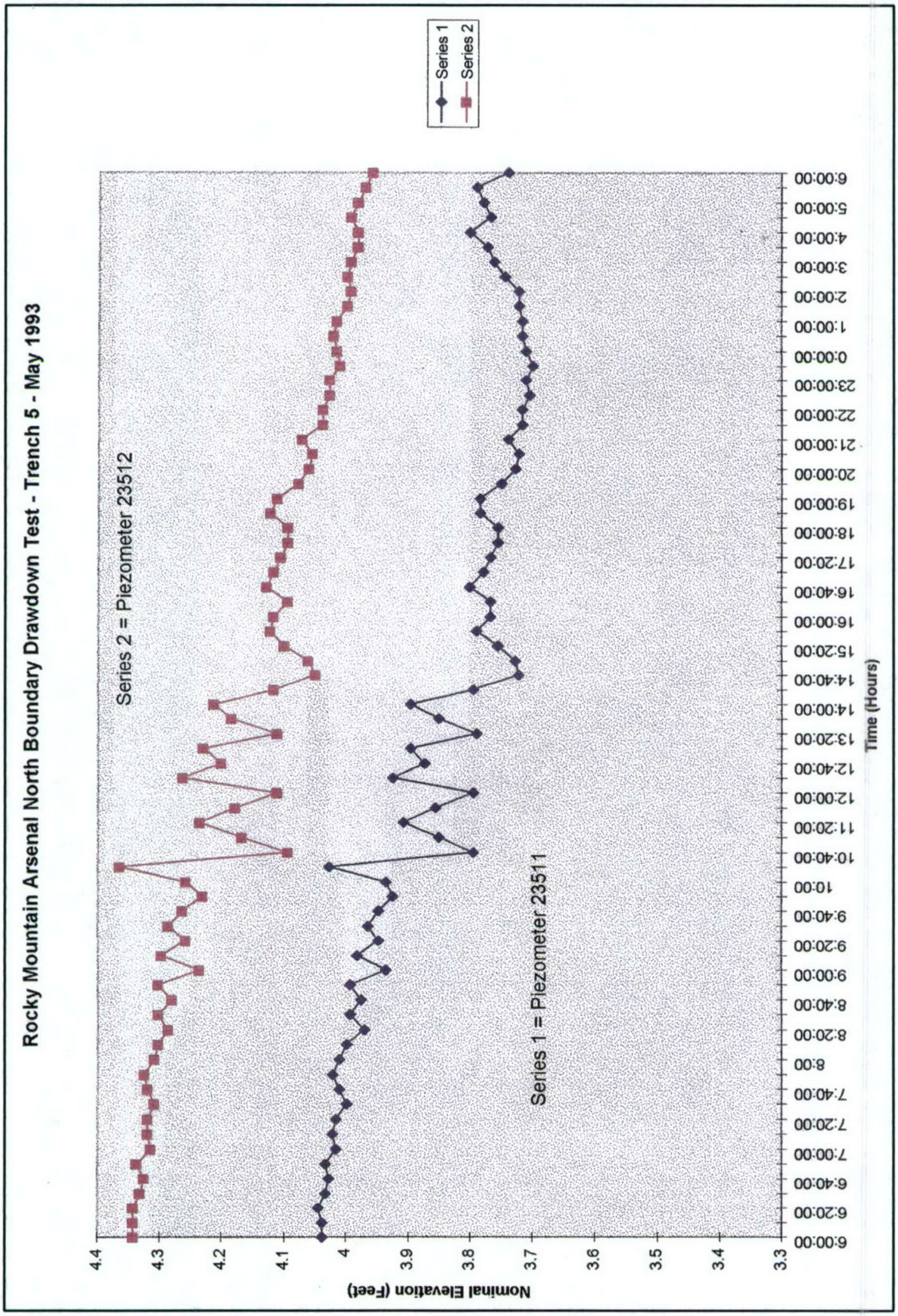
Time (Hours)
Piezometer 23514
Series 1



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Series 1 = Piezometer 23511
Series 1
Series 2
Nominal Elevation (Feet)
Time (Hours)
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4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
6:00:00
6:20:00
6:40:00
7:00:00
7:20:00
7:40:00
8:00
8:20:00
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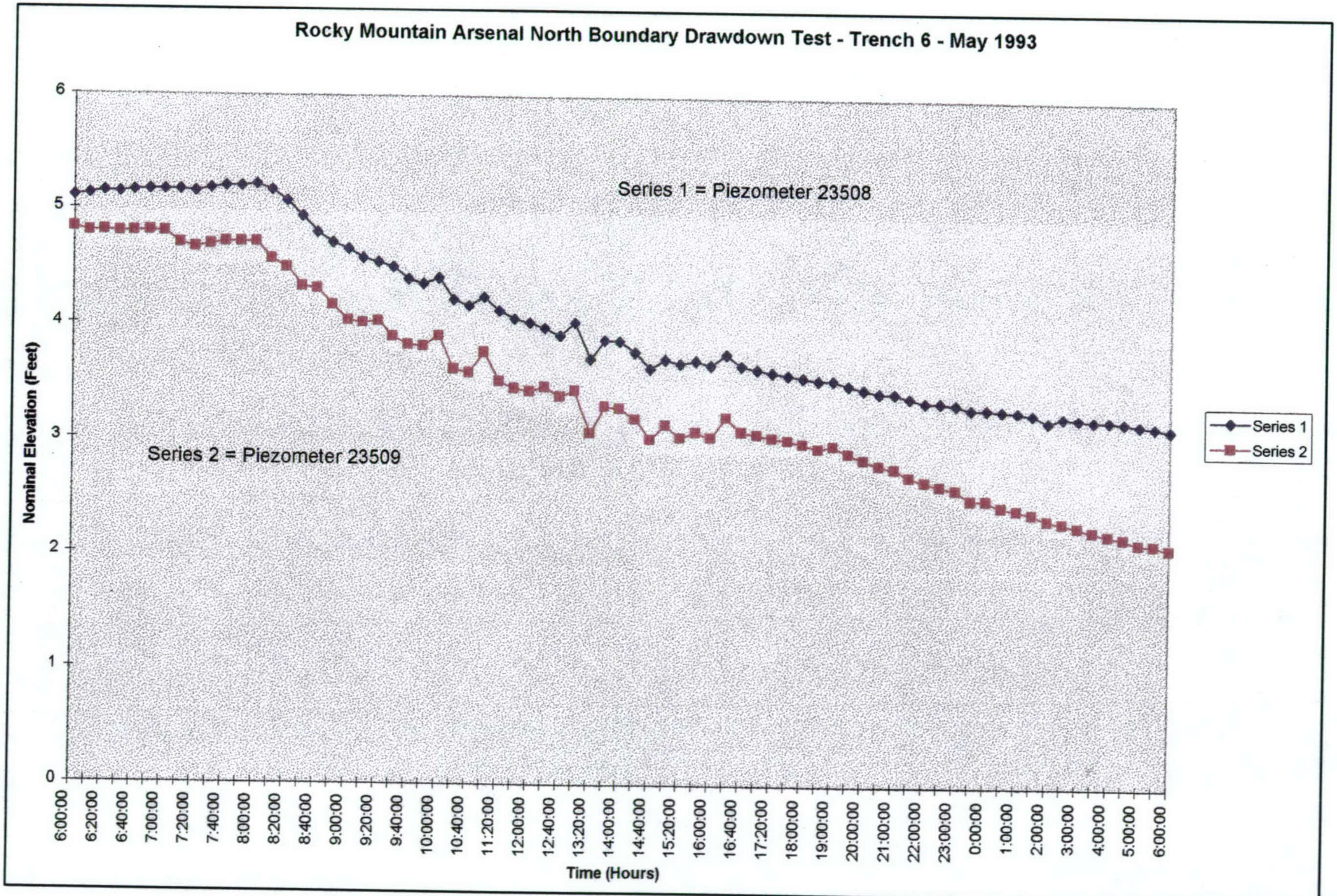
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Series 2 = Piezometer 23509
Nominal Elevation (Feet)
Time (Hours)
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Series 2
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2
3
4
5
6
6:00:00
6:20:00
6:40:00
7:00:00
7:20:00
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8:00:00
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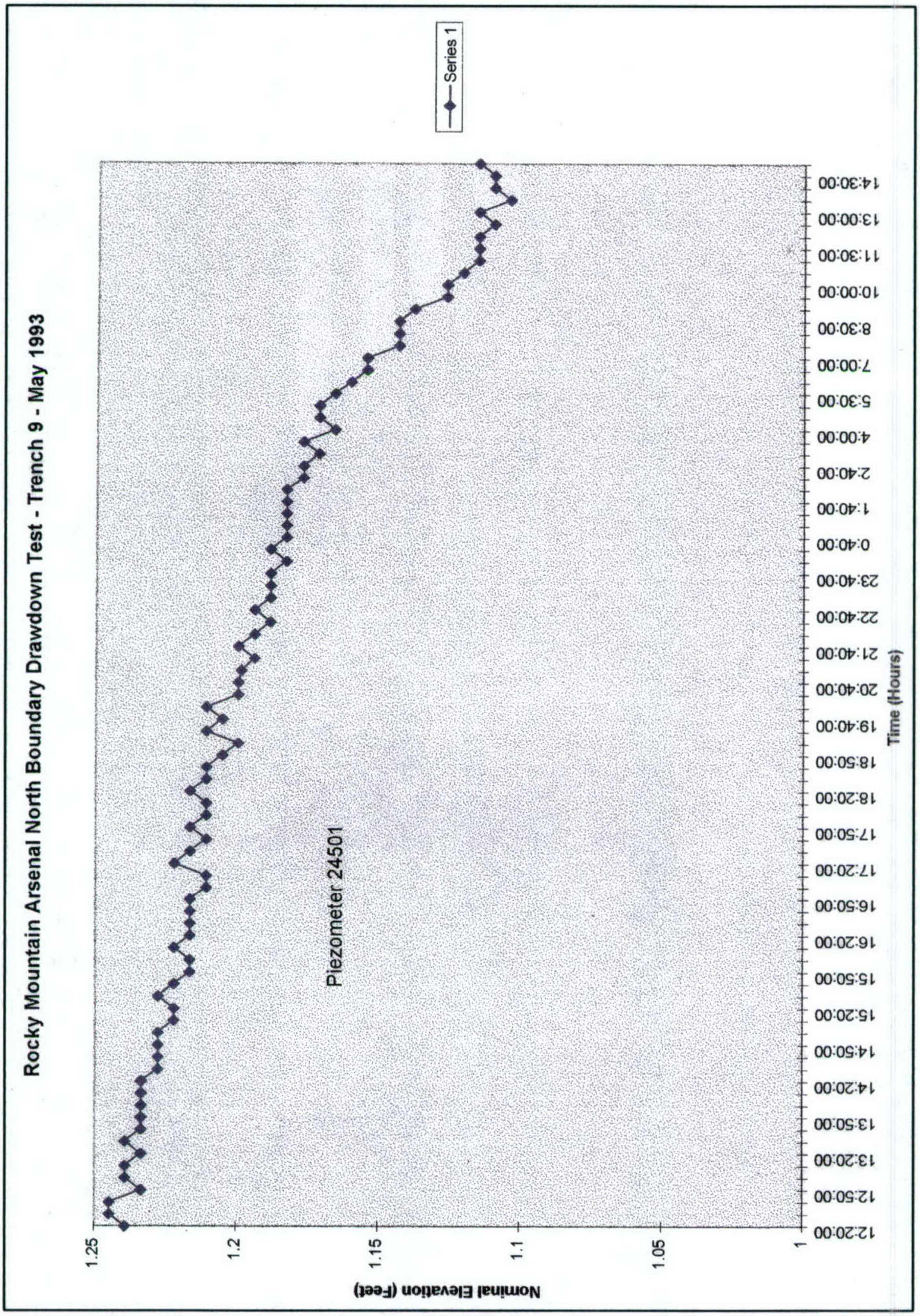
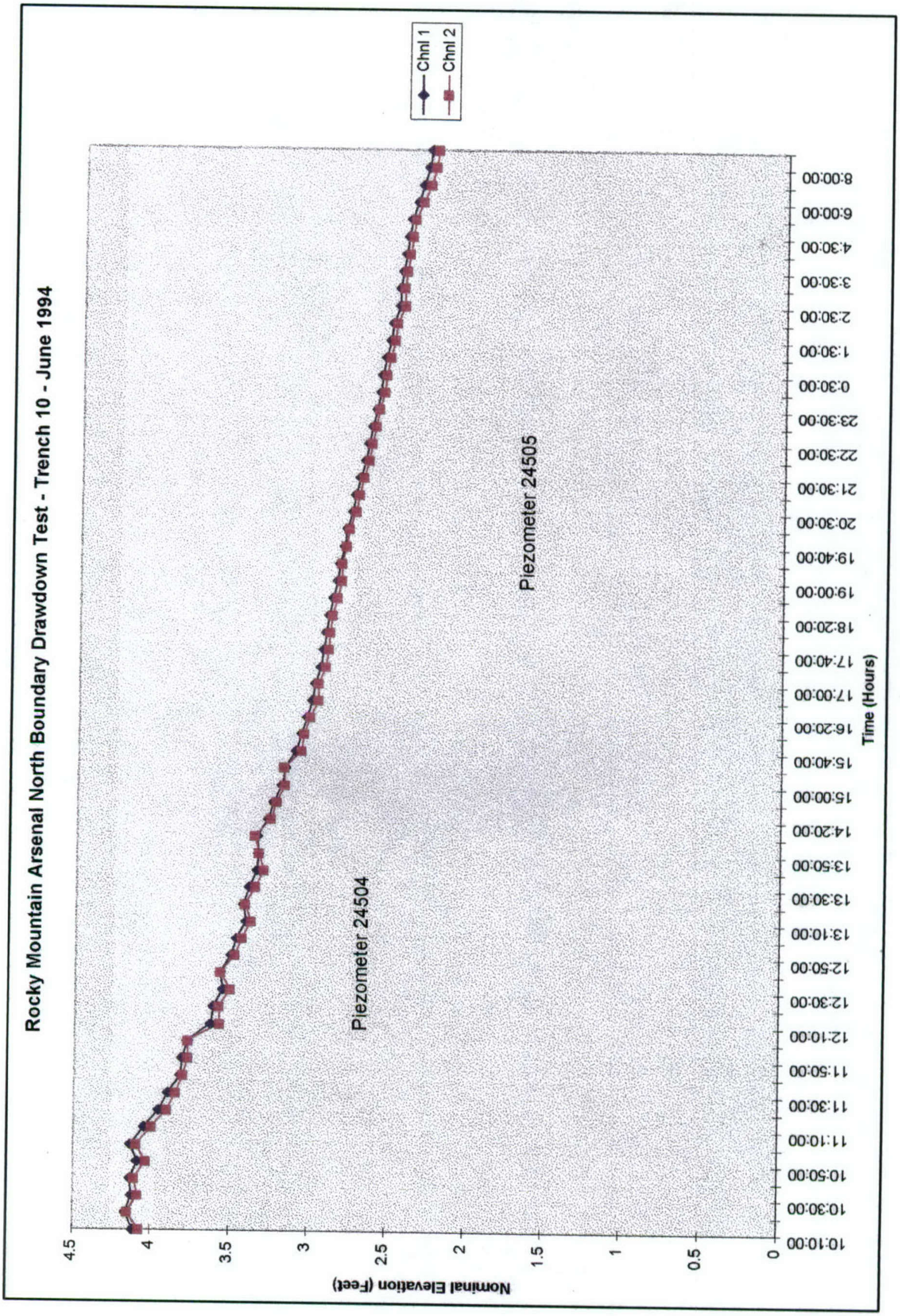
16:40:00
17:20:00
18:00:00
19:00:00
20:00:00
21:00:00
22:00:00
23:00:00
0:00:00
1:00:00
2:00:00
3:00:00
4:00:00
5:00:00
6:00:00



Rocky Mountain Arsenal North Boundary Drawdown Test - Trench 9 - May 1993
Piezometer 24501
Series 1
Nominal Elevation (Feet)
1.25
1.2
1.15
1.1
1.05
1
Time (Hours)
12:20:00
12:50:00
13:20:00
13:50:00
14:20:00
14:50:00
15:20:00
15:50:00
16:20:00
16:50:00
17:20:00
17:50:00
18:20:00
18:50:00
19:40:00
20:40:00
21:40:00
22:40:00
23:40:00
0:40:00
1:40:00
2:40:00
4:00:00
5:30:00
7:00:00
8:30:00
10:00:00
11:30:00
13:00:00
14:30:00


Rocky Mountain Arsenal North Boundary Drawdown Test - Trench 10 - June 1994
Nominal Elevation (Feet)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (Hours)
10:10:00
10:30:00
10:50:00
11:10:00
11:30:00
11:50:00
12:10:00
12:30:00
12:50:00
13:10:00
13:30:00
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14:20:00
15:00:00
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22:30:00
23:30:00
0:30:00
1:30:00
2:30:00
3:30:00
4:30:00
6:00:00
8:00:00
Piezometer 24504
Piezometer 24505
Chnl 1
Chnl 2

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14. ABSTRACT

This report summarizes hydrogeologic investigations completed in 2002 on the recharge trenches at the North Boundary Containment Treatment System (NBCTS) at Rocky Mountain Arsenal (RMA), located in Commerce City, CO. The NBCTS is a 6,740-ft (2,054-m)-long multicomponent system that precludes off-site movement of contaminated water at the north boundary of RMA. It consists of a slurry wall, dewatering wells, treatment plant, and recharge trenches.

Prior to 1988, treated water was recharged back to the shallow unconfined aquifer by means of recharge wells. Over time, these wells lost their efficiency as the result of microbial fouling, and 15 recharge trenches were constructed along the length of the system to replace the recharge wells. To address concern regarding the continued hydraulic efficiency of the system, methodologies were developed to evaluate, on a year-to-year basis, trench hydraulic conductivity. Initially, hydraulic conductivity was determined on individual trenches and trench sets according to Darcy's Law using averaged values of recharge and hydraulic gradient, as available in annual assessment reports.

(Continued)

15. SUBJECT TERMS
Containment and treatment system
Denver Formation
Falling head test
Recharge trenches
Rocky Mountain Arsenal

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14. ABSTRACT

In 1992, field testing was initiated, which consisted of cessation of recharge to a given trench and measurement of the decline or water levels in the trenches with time. These tests were modeled after field slug tests, and the resulting drawdown rates, which were proportional to hydraulic conductivity, were considered to provide relative information on changes in trench condition with time.

In 1996, testing was again revised, and the earlier methods were reestablished except that water levels were measured in the field and recharge (now a known quantity) was held constant during the water level reading. Having established steady-state conditions, hydraulic conductivity could be calculated for each trench on the basis of Darcy's Law. After 8 years of testing (including all methods), test results were remarkably uniform. Hydraulic conductivity calculations (averaged and real time) were determined to be within an order magnitude, as were drawdown rates. On the basis of hydraulic conductivity values, the trenches are performing similarly to well-sorted sands or well-sorted gravels.